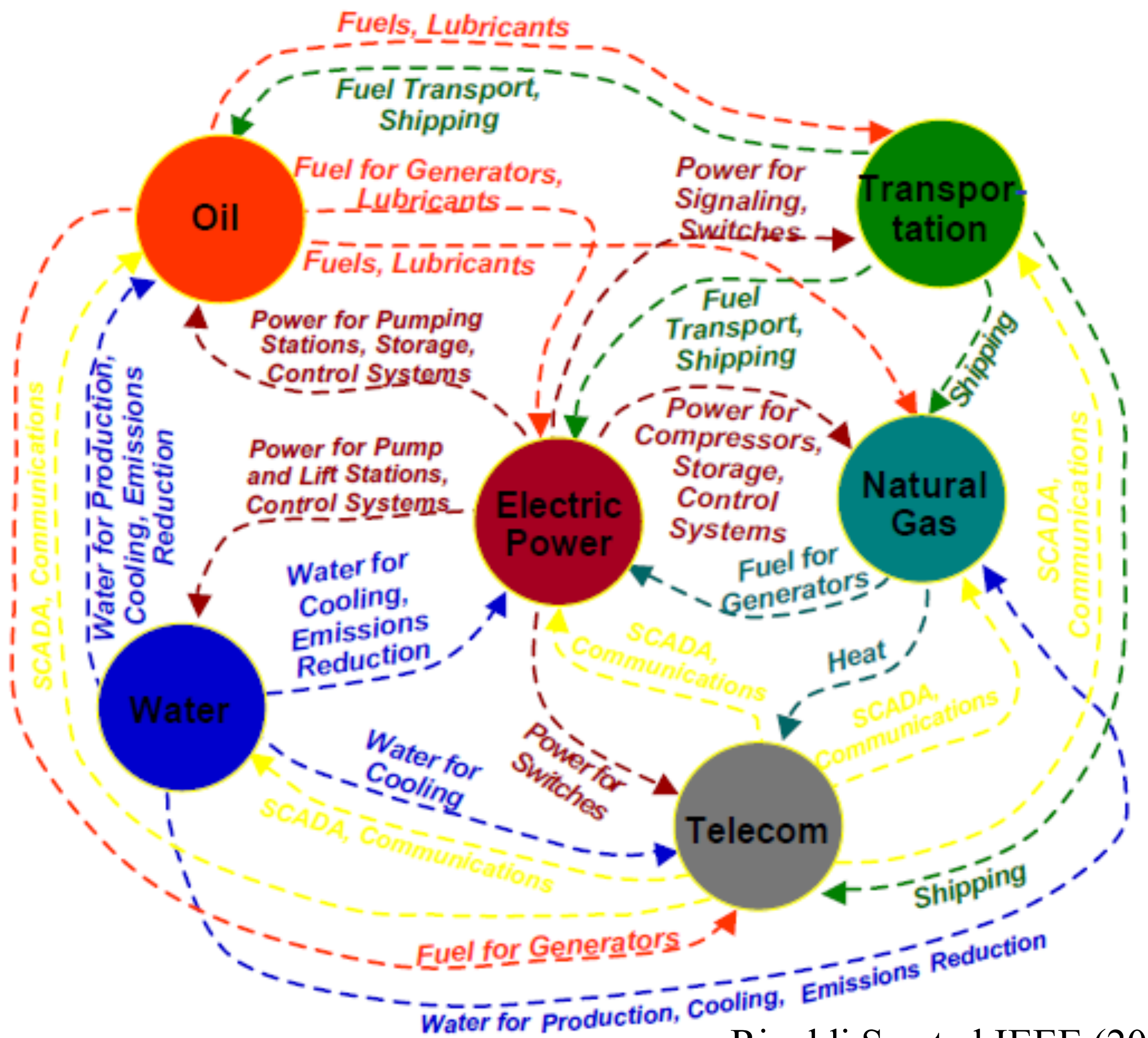
How interdependent are infrastructures?



Rinaldi S, et al IEEE (2001)

VOLUME 279
NUMBER 73
Suggested retail price
$1.00
$1.50 outside of
Metro Boston
*

The Boston Globe

A NEW WEAK

TODAY: *Partly sunny and colder. H 37-42. Low 27-32.*
TOMORROW: *Mostly sunny, milde High 42-47. Low 32-37.*
HIGH TIDE: *6:42 a.m., 7:25 p.m.*
SUNRISE: *6:59* SUNSET: *6:49*
FULL REPORT: PAGE B13

MONDAY, MARCH 14, 2011

Cascading disaster in Japan

Blast shakes a second reactor death toll soar

By Martin Fackler
and Mark McDonald
NEW YORK TIMES

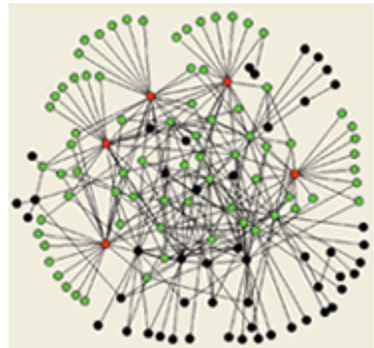
SENDAI, Japan — Japan reel from a rapidly unfolding disaster epic scale yesterday, pummeled by t death toll, destruction, and homele ness caused by the earthquake a tsunami and new hazards from da aged nuclear reactors. The prime m ister called it Japan's worst crisis sir World War II.

Japan's $5 trillion economy, t world's third largest, was threaten with severe disruptions and partial p ralysis as many industries shut do temporarily. The armed forces and v unteers mobilized for the far more gent crisis of finding survivors, eva ating residents near the strick power plants and caring for the v tims of the record 8.9 magnitu quake that struck on Friday.

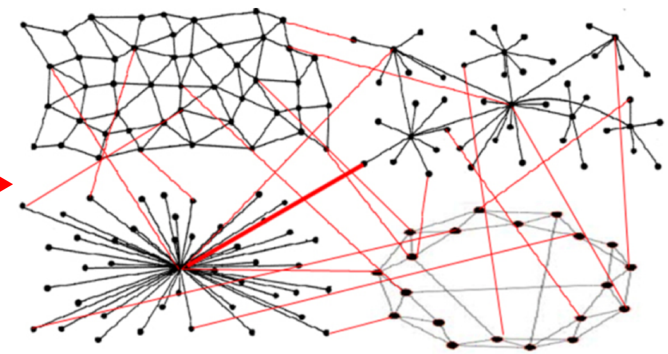
The disaster has left more th 10,000 dead, many thousands hom less, and millions without water, po er, heat, or transportation.

From Single Network to Network of Networks

2000



2010



Collaboration:

Amir Bashan, BIU
Sergey Buldyrev, NY
Michael Danziger, BIU
J. Gao: Northeastern
Orr Levy, BIU
Roni Parshani: BIU
Louis Shektman, BIU
Antonio Majdanzic, BU
H. E. Stanley, BU
Dong Zhou, BIU
PARTIAL LIST

Shlomo Havlin

multilevel
multilayer
multiplex

Buldyrev et al, Nature, 464, 1025 (2010)
Parshani et al, PRL ,105, 0484 (2010)
Parshani et al, PNAS, 108, 1007 (2011)
Gao et al, PRL, 107, 195701 (2011)
Gao et al, Nature Phys.,8, 40 (2012)
Wei Li et al, PRL, 108, 228702 (2012)
Bashan et al, Nature Phys. 9, 667 (2013)
Majdanzik et al Nature Comm. **7**, 10850 (2016)
Xin Yuan et al, PNAS **114**, 3311 (2017)

Electric grid,
Communication
Transportation
Services …..

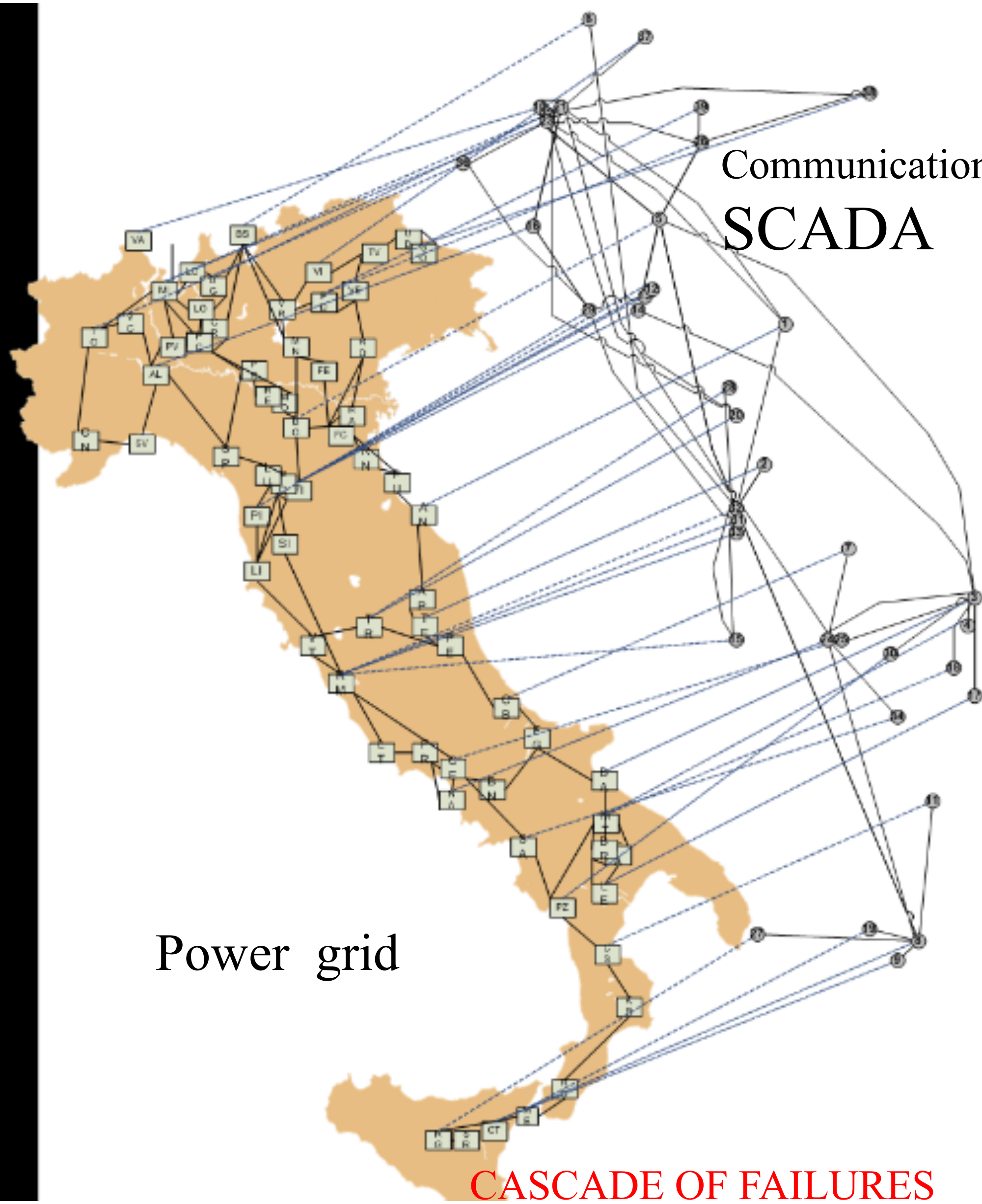
Two types of links:
1. Connectivity
2. Dependency

Cascading failures-abrupt transition

Blackout in Italy (28 September 2003)

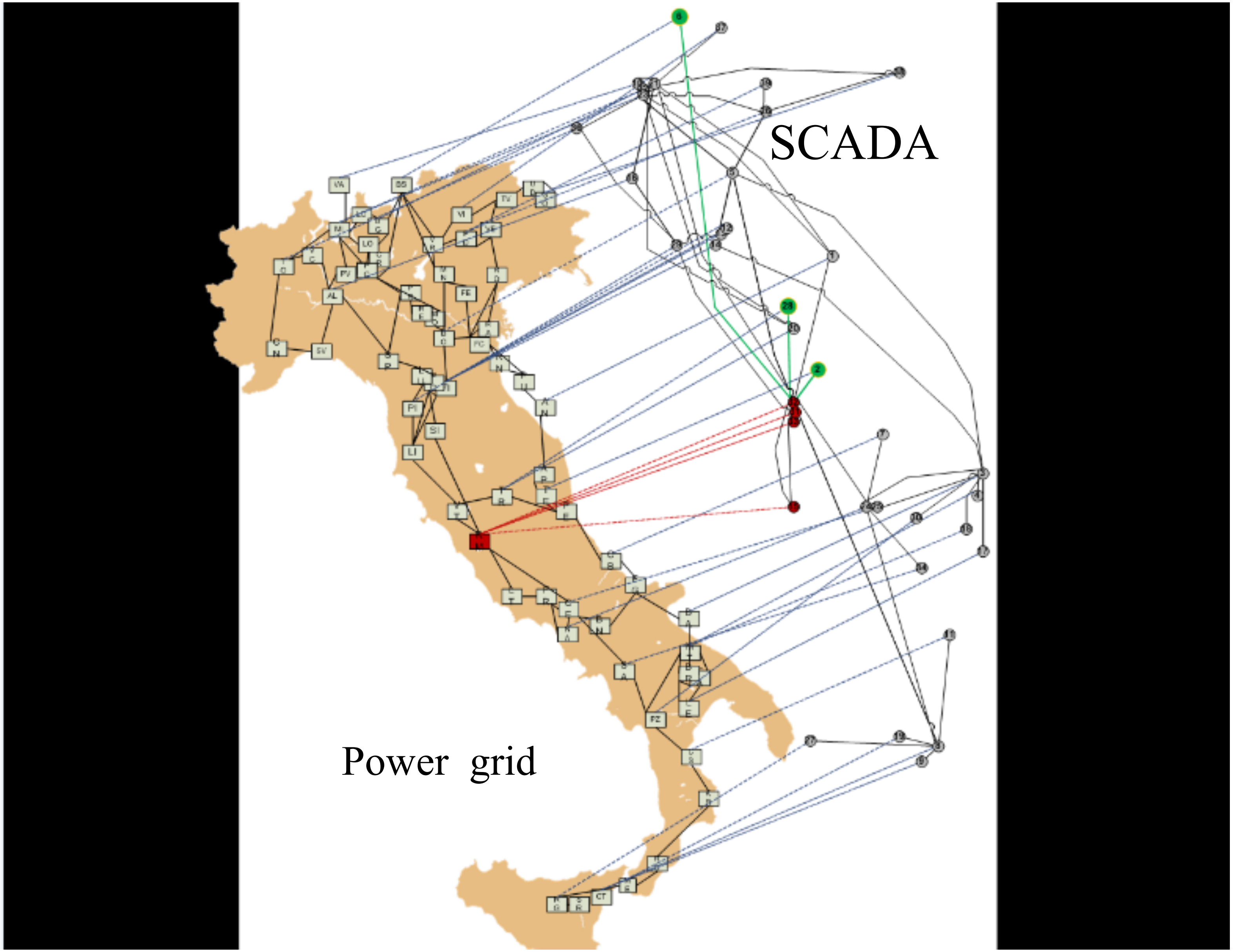
Cyber Attacks- CNN Simulation (2010)

Rosato et al Int. J. of Crit. Infrastruct. 4, 63 (2008)



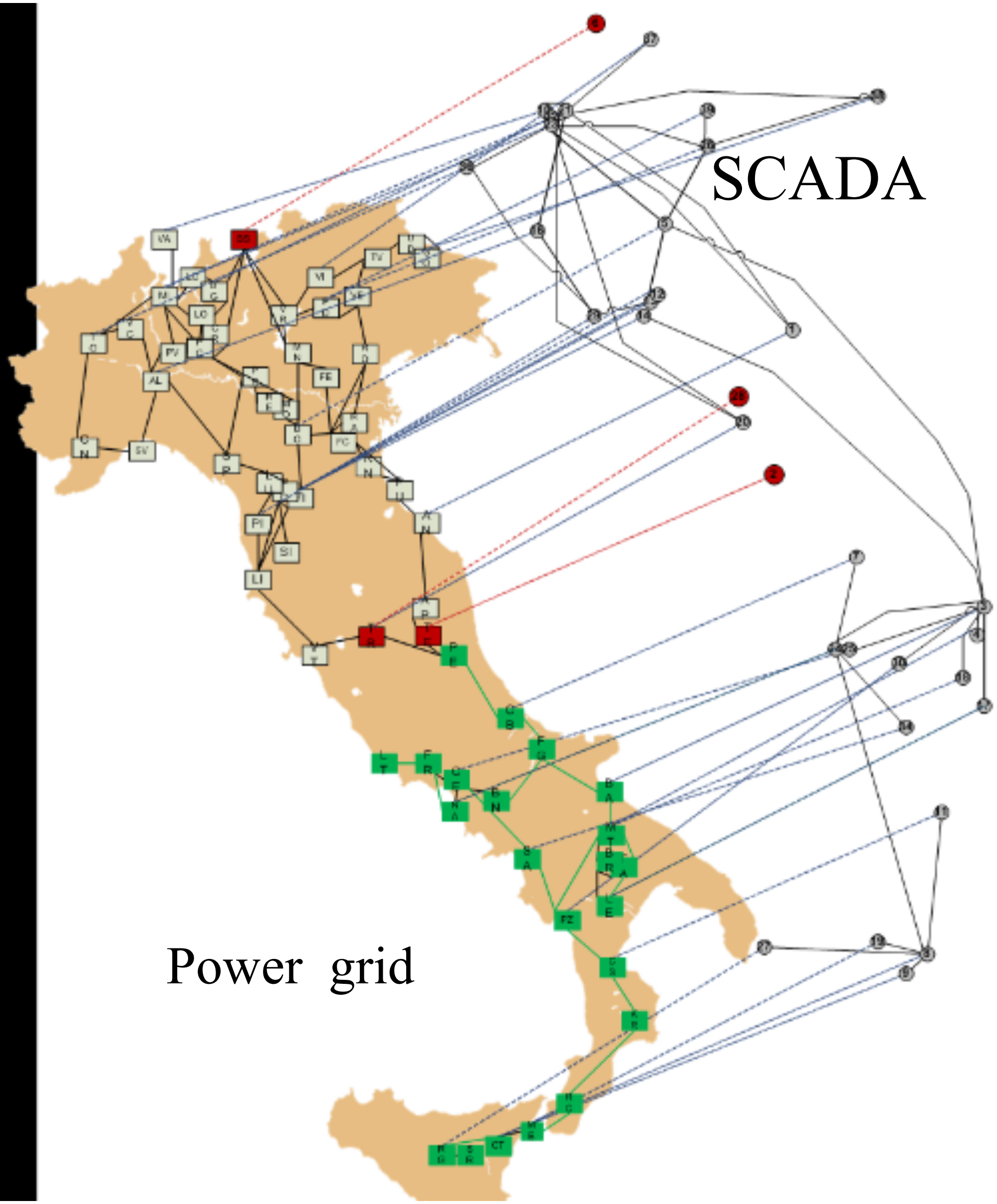
Railway network, health care systems, financial services, communication systems

Blackout in Italy (28 September 2003)

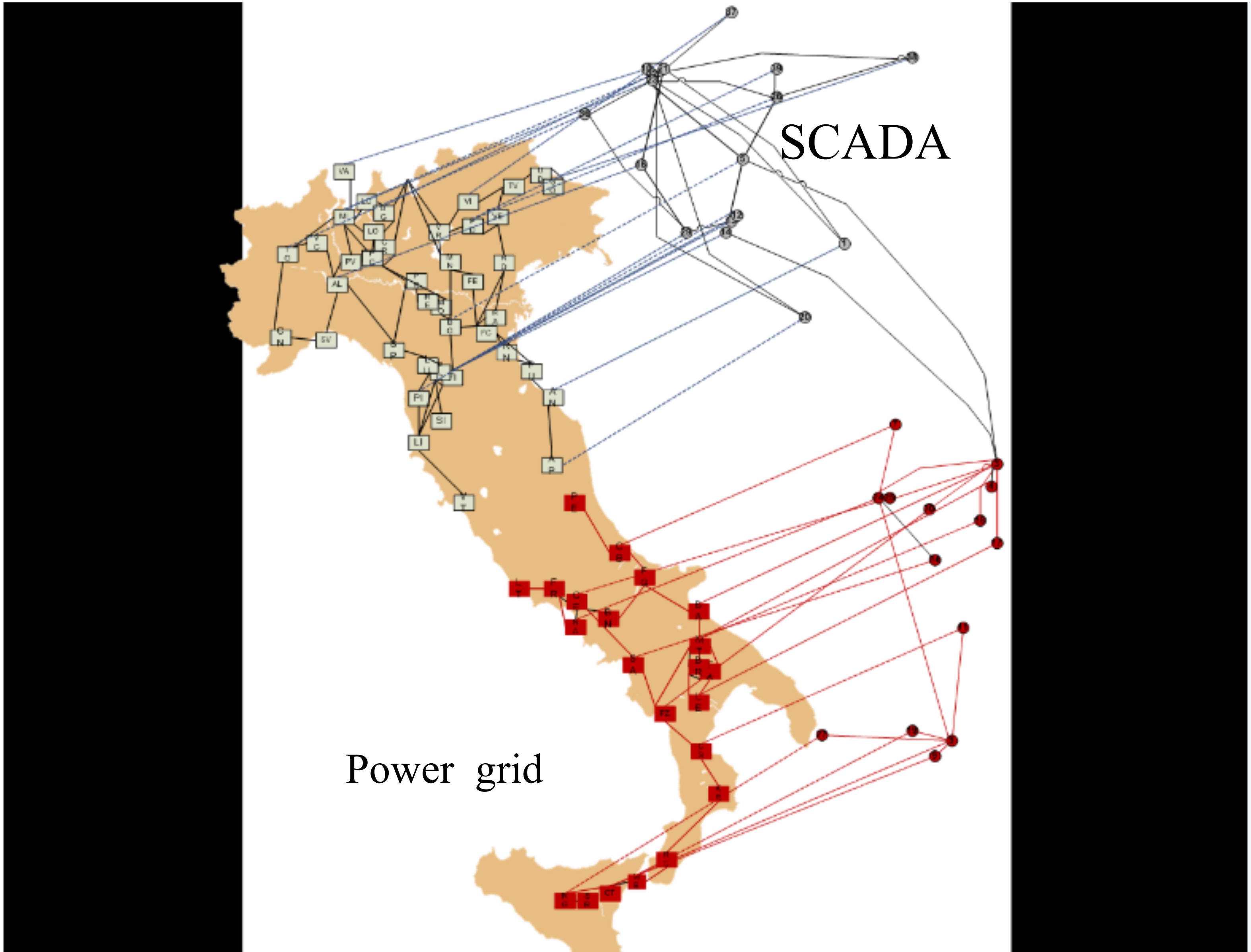


SCADA=Supervisory Control And Data Acquisition

Blackout in Italy (28 September 2003)



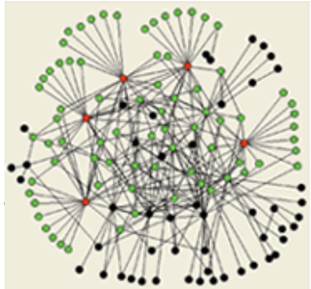
Blackout in Italy (28 September 2003)



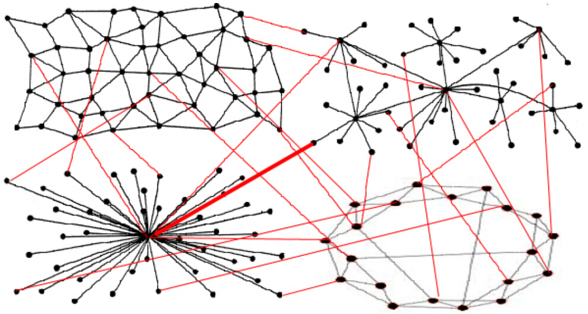
CNN SCENARIO

Interdependent Networks

- Until 2010 studies focused on a single network which is isolated AND does not interact or influenced by other systems.

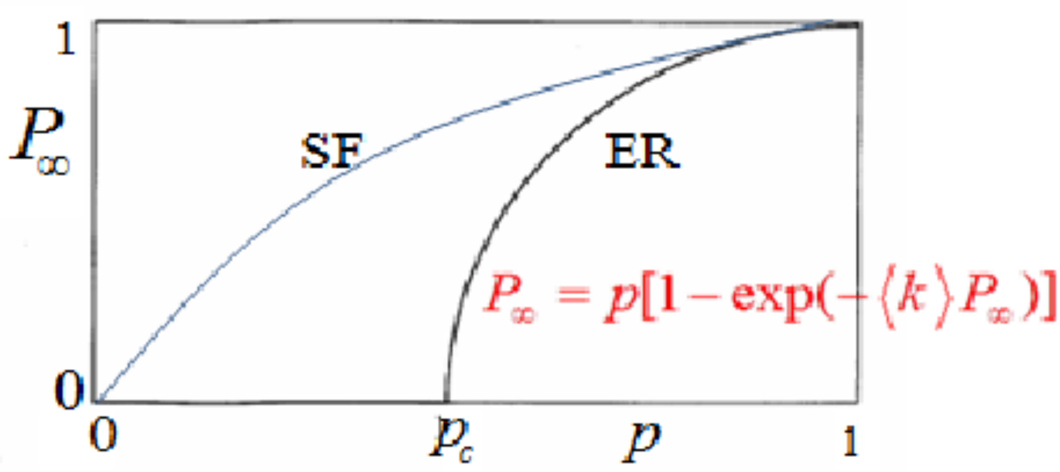


- Isolated systems rarely occur in nature or in technology -- analogous to non-interacting particles (molecules, spins).

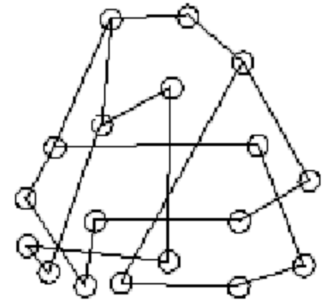


- Results for interacting networks are strikingly different from those of single networks.

Percolation of Network-Giant Component P_∞

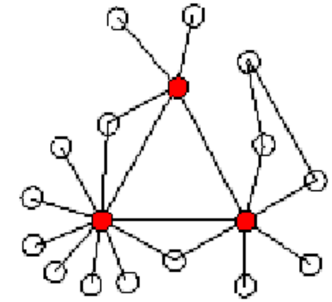


Exponential



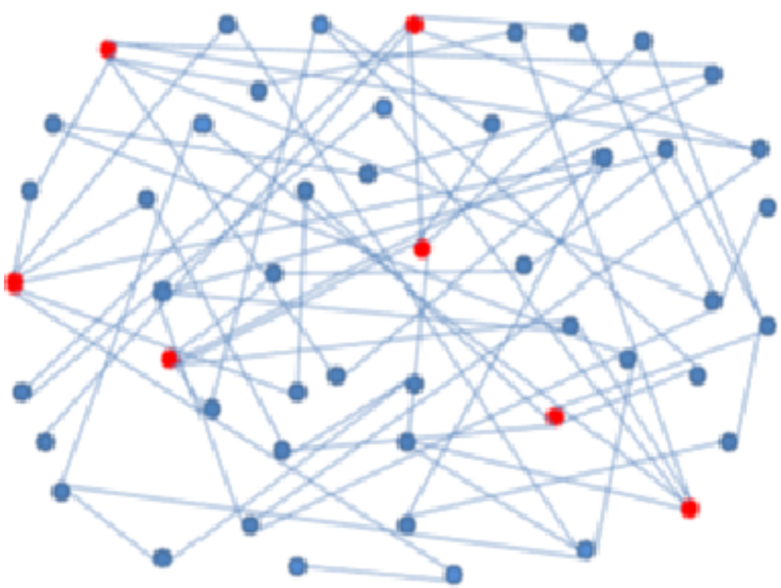
$$P(k) = e^{-\langle k \rangle} \frac{\langle k \rangle^k}{k!}$$

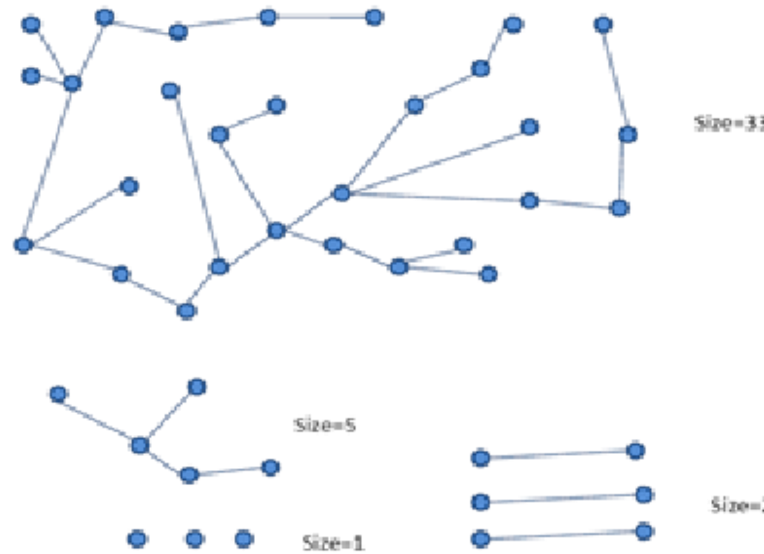
Scale-free



$$P(k) = \begin{cases} ck^{-\lambda} & m \le k \le K \\ 0 & otherwise \end{cases}$$

Scale-free network: N=50; λ=2.5 – attacking 7 nodes p=43/50





Comparing single and coupled networks: Robustness

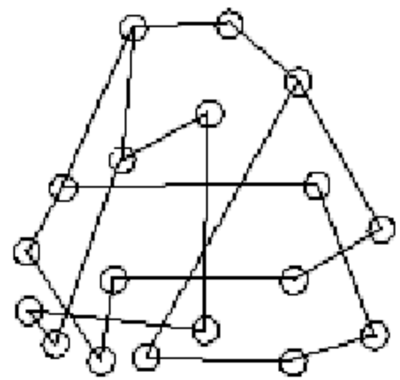
Remove randomly (or targeted) a fraction $1-p$ nodes

P_∞ Size of the largest connected component (cluster)

p_c Breakdown threshold

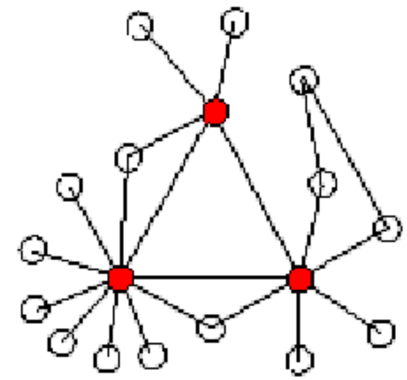
Single networks:
Continuous transition

Exponential (ER)

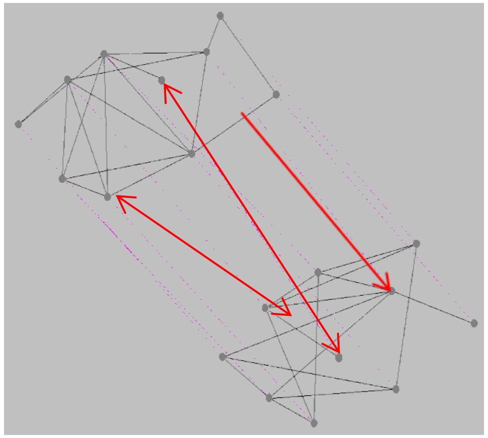


$$P(k) = e^{-\langle k \rangle} \frac{\langle k \rangle^k}{k!}$$

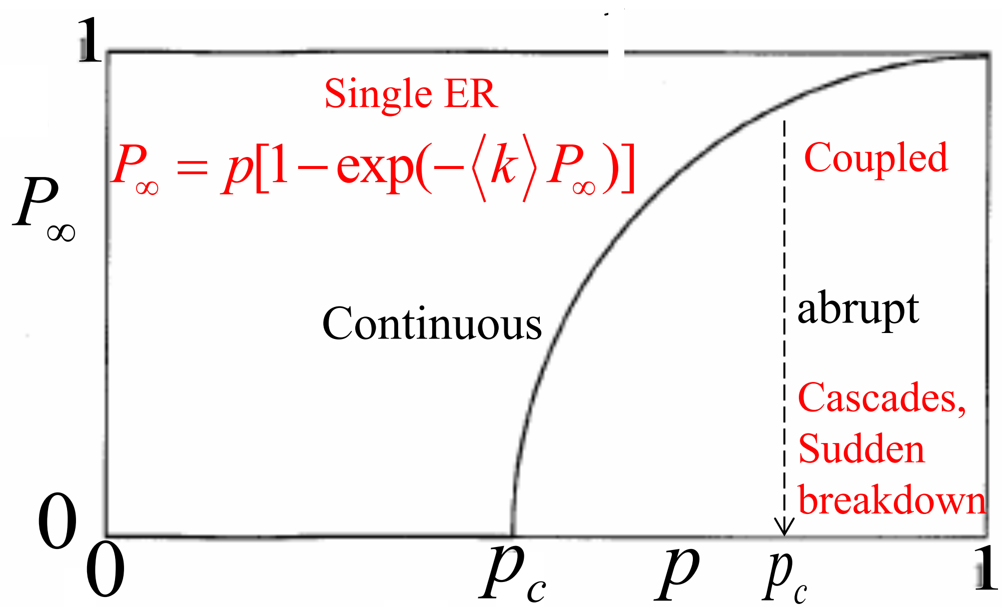
Scale-free (SF)



$$P(k) = \begin{cases} ck^{-\lambda} & m \le k \le K \\ 0 & otherwise \end{cases}$$



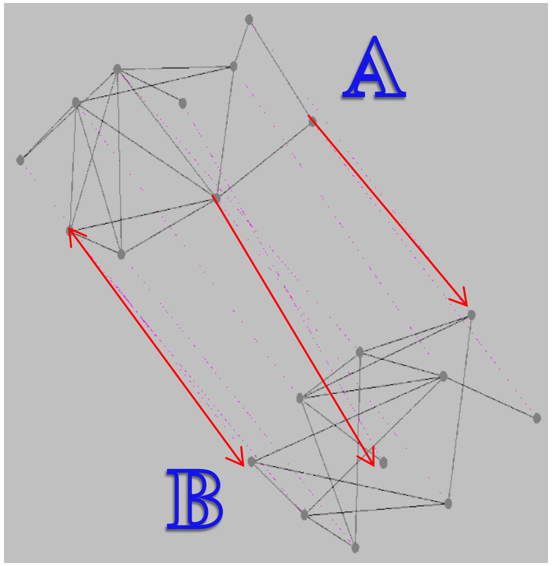
Coupled networks:
New paradigm-Abrupt transition
Cascading Failures



Message: our world is extremely unsafe!

GENERALIZATION: PARTIAL DEPENDENCE:

Theory and Simulations

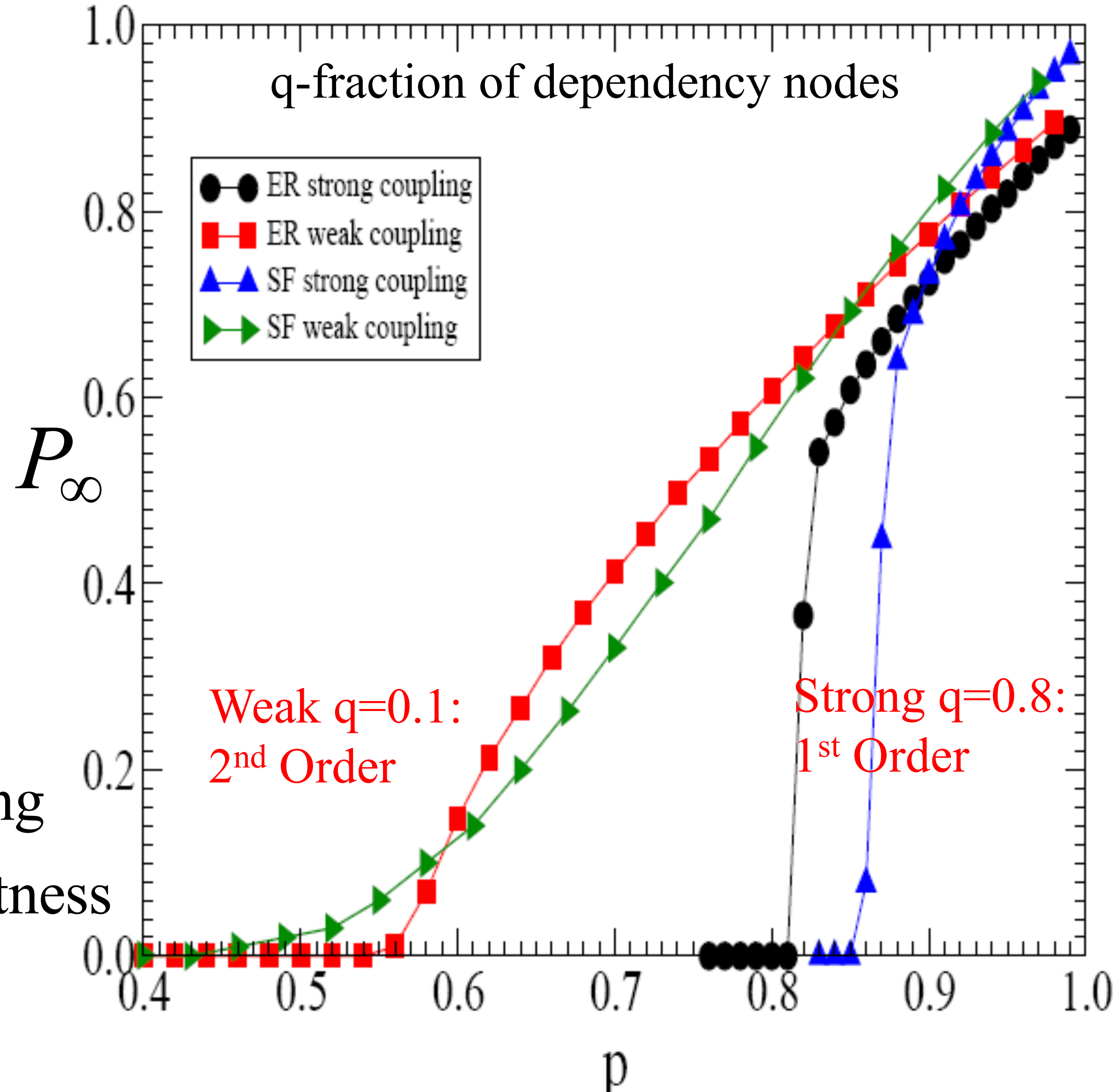


Parshani, Buldyrev, S.H.
PRL, **105**, 048701 (2010)

$q_c \cong 0.2$ for random coupling

$q_c \rightarrow 0.9$ for optimal robustness

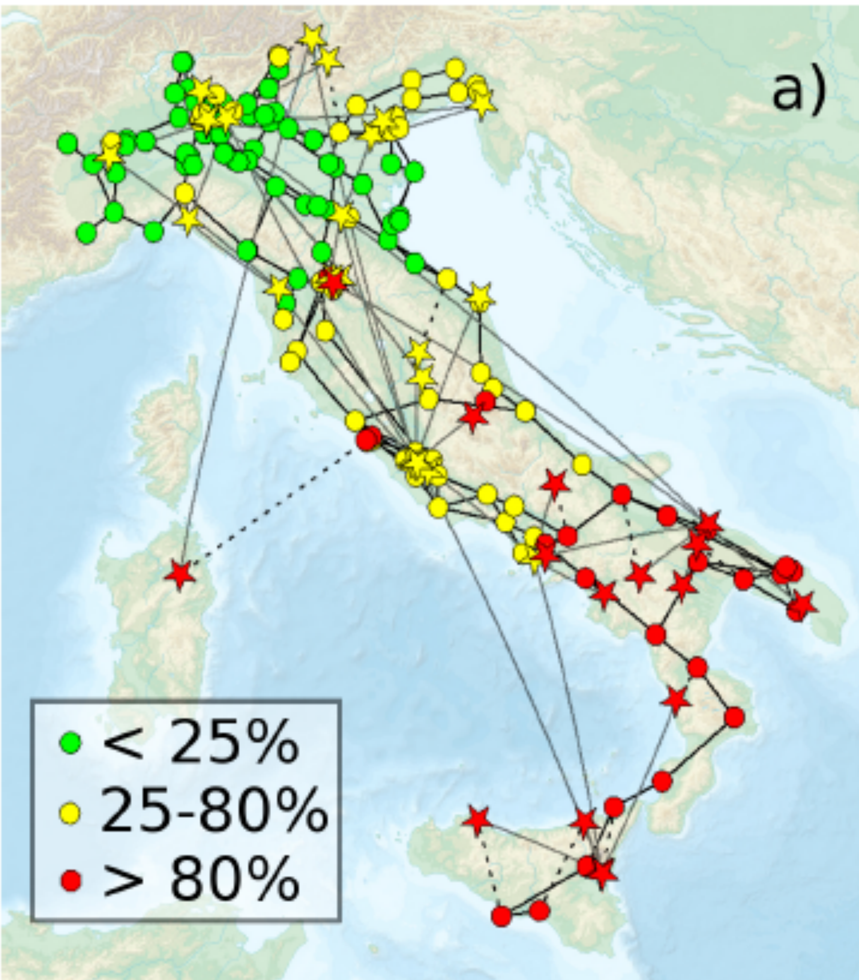
Schneider et al
Scientific Reports (2013)



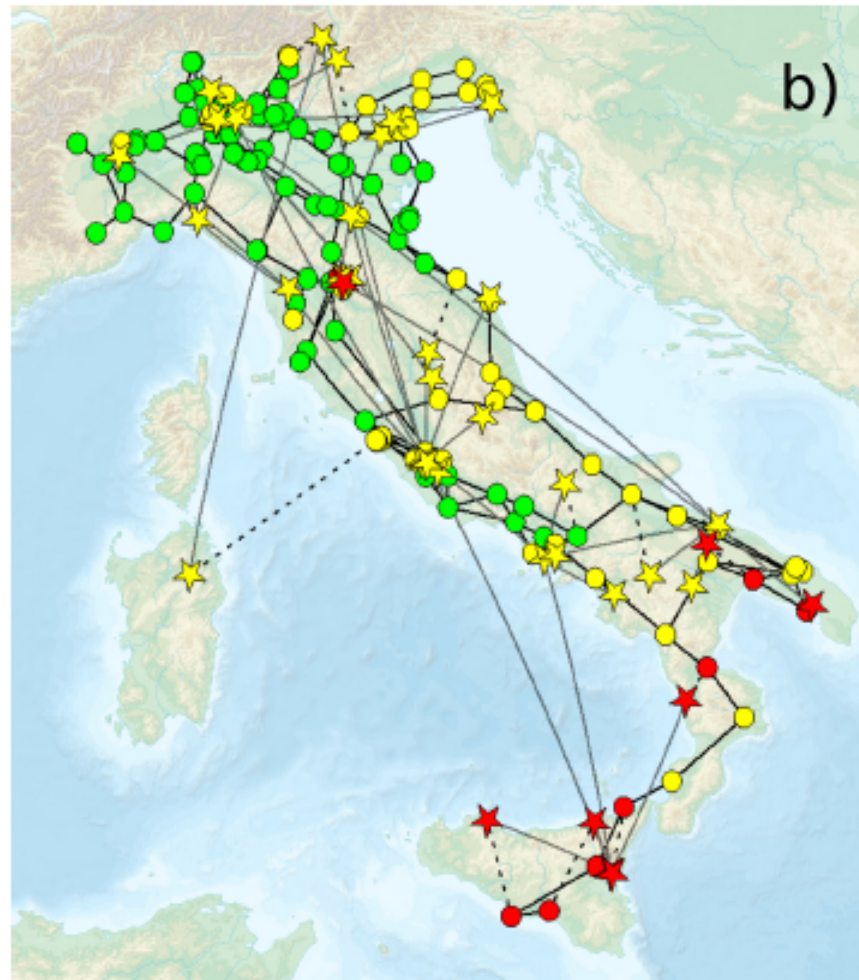
Designing Robust Coupled Networks:

Italy 2003 blackout

Random interdependencies



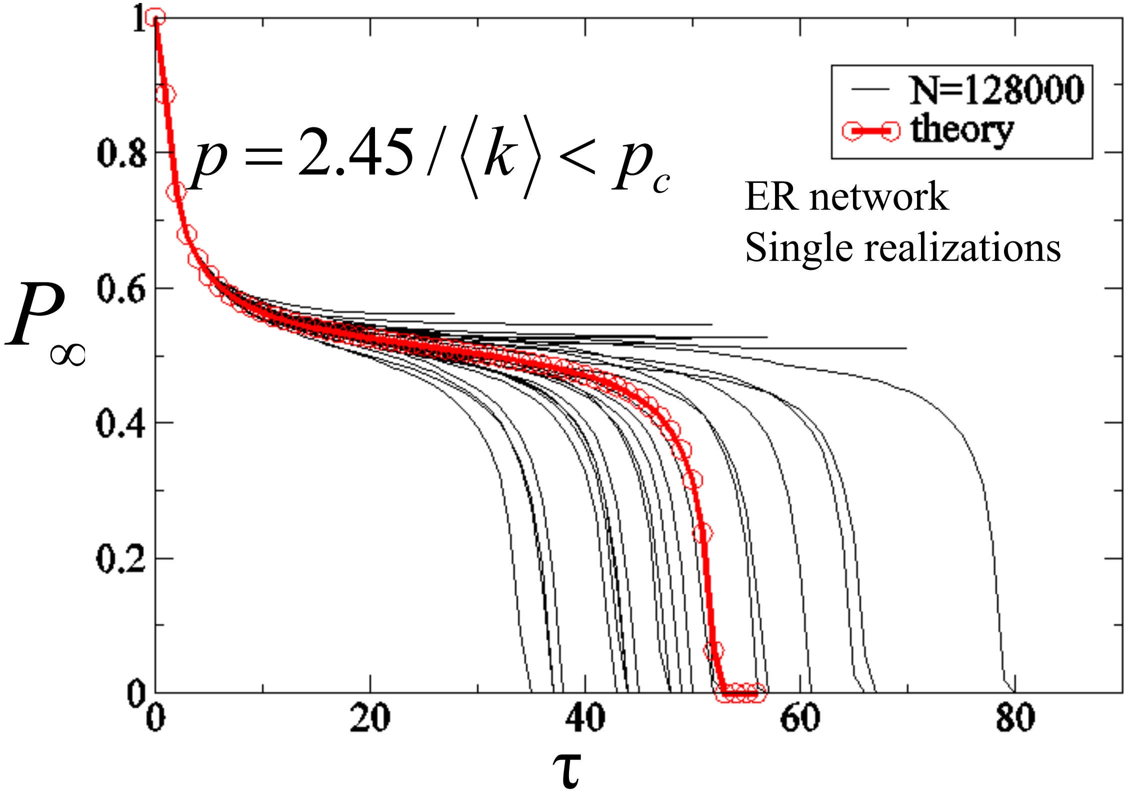
Nearly optimal interdependencies



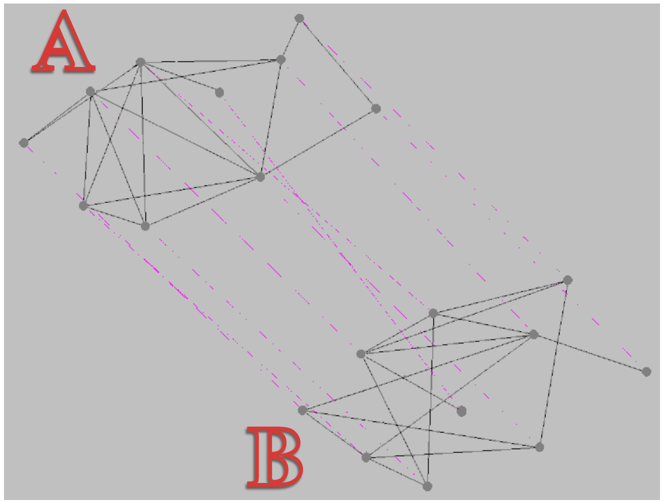
Schneider, Araujo, Havlin , Herrmann, Designing Robust Coupled Networks, Scientific Reports (2013)

RESULTS: THEORY and SIMULATIONS: ER Networks

P_∞ after τ-cascades of failures



Removing 1-p nodes in A



Catastrophic cascades just below p_c

ABRUPT TRANSITION (1^{st} order)

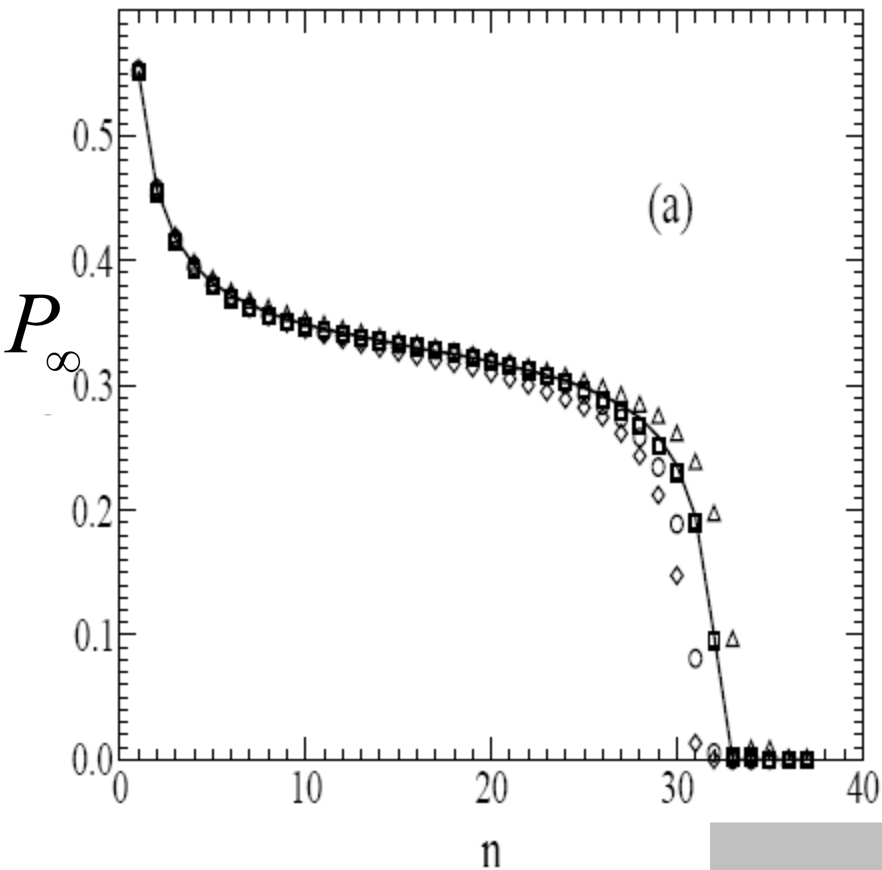
$p_c = 2.4554/\langle k \rangle$ For a single network $p_c = 1/\langle k \rangle$

$\langle k \rangle_{\min} = 2.4554$ for single network $\langle k \rangle_{\min} = 1$

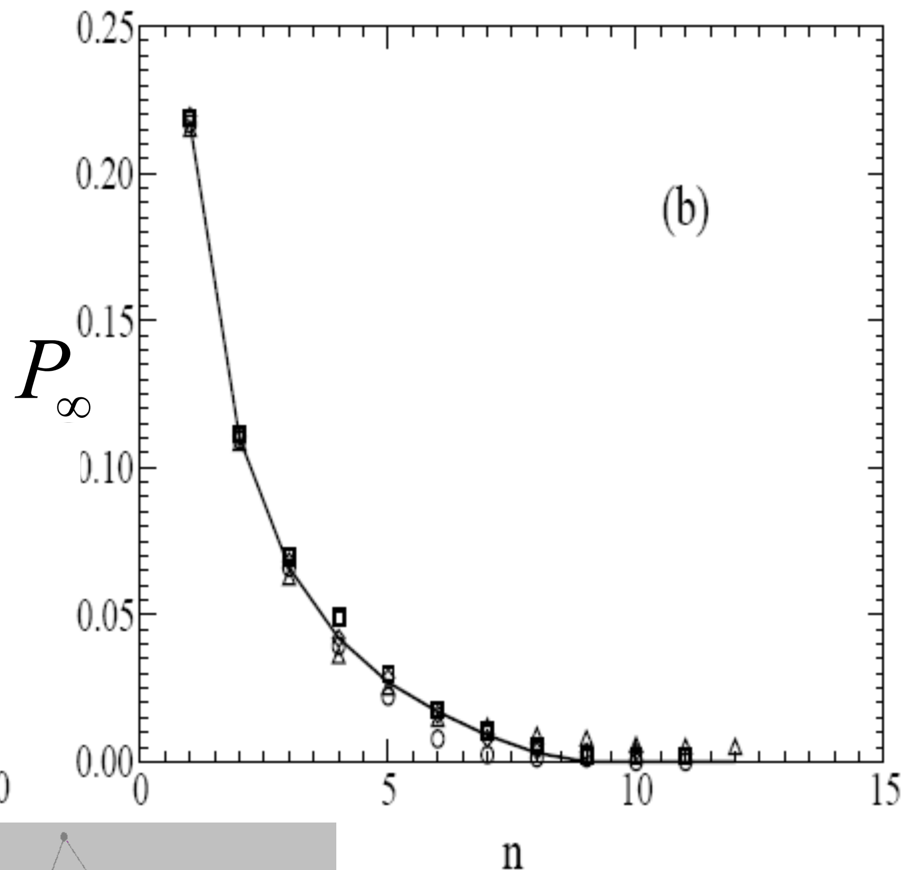
$\langle \tau \rangle \sim N^{1/3}$

Dong Zhou et al (2013)

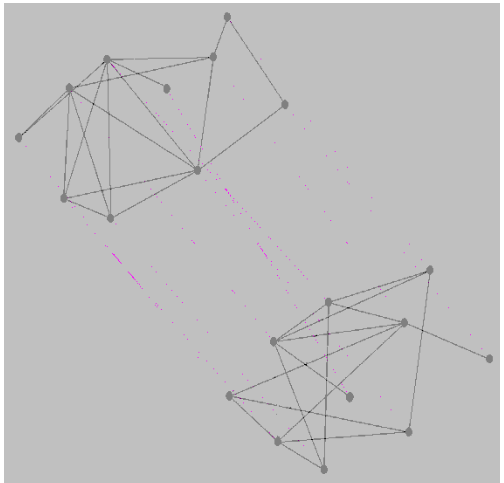
Strong Coupling



Weak Coupling



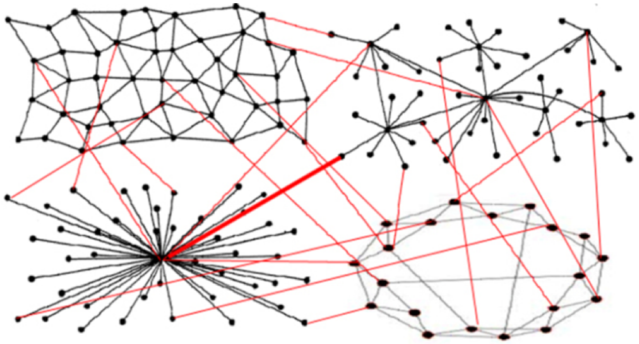
q=0.8

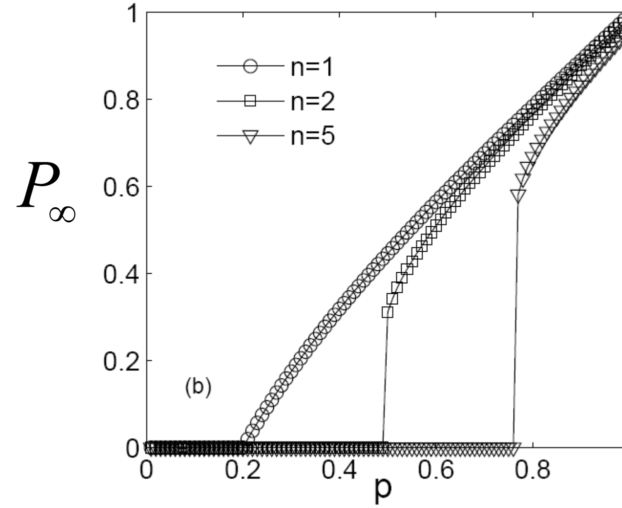


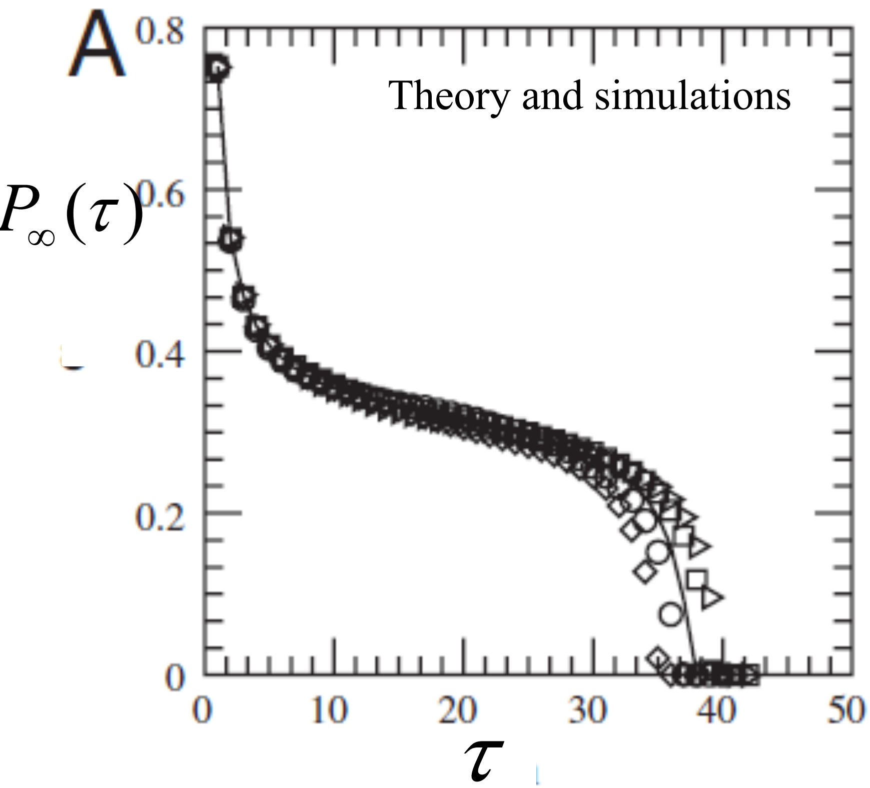
q=0.1

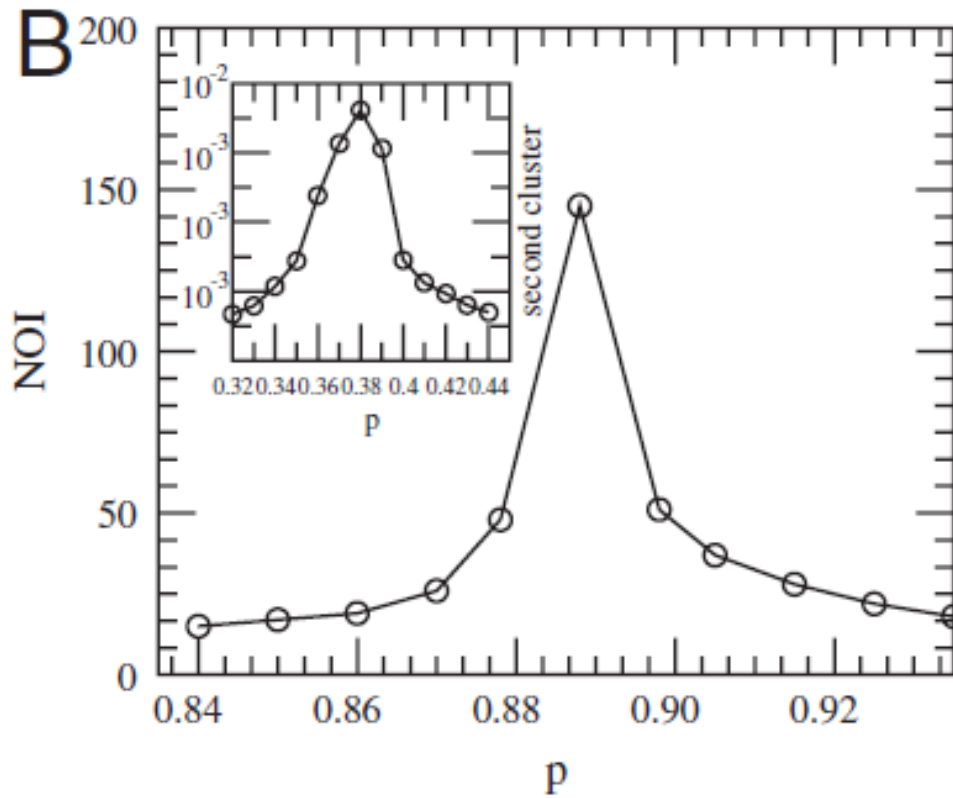
Interdependent Networks

Determining p_c in simulations



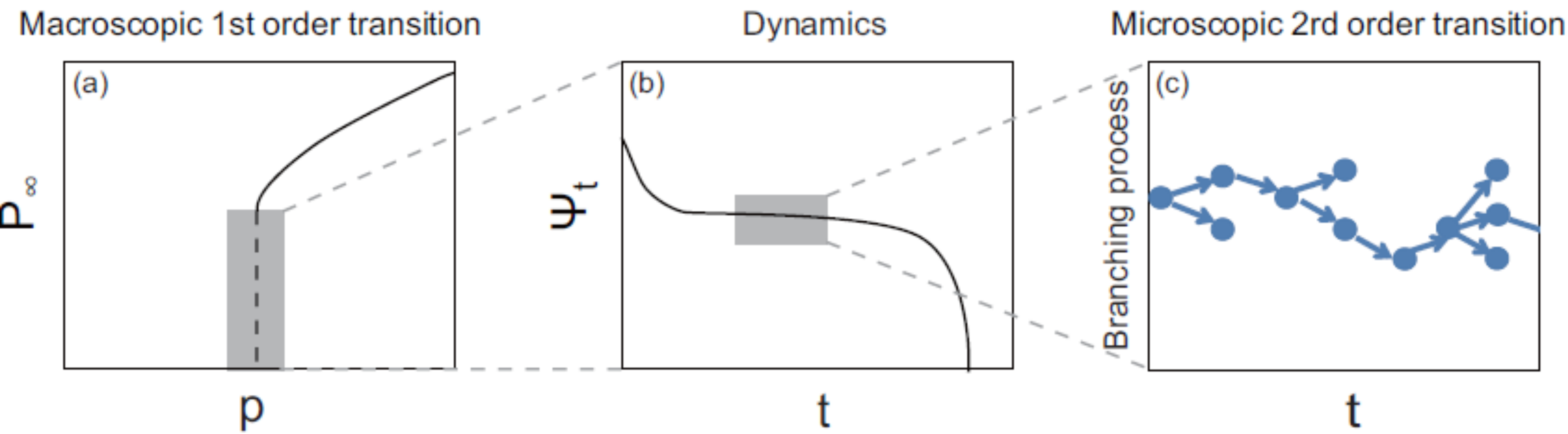




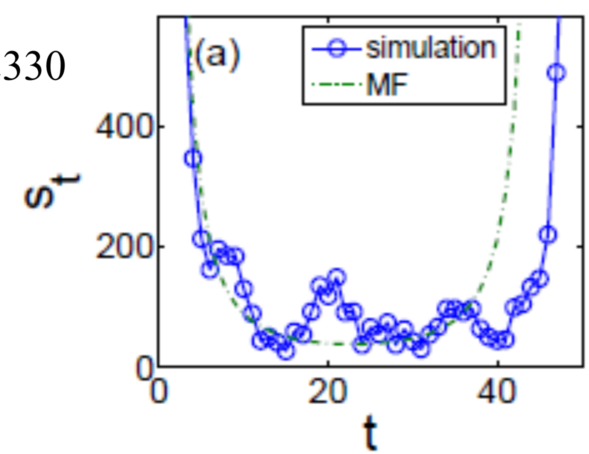


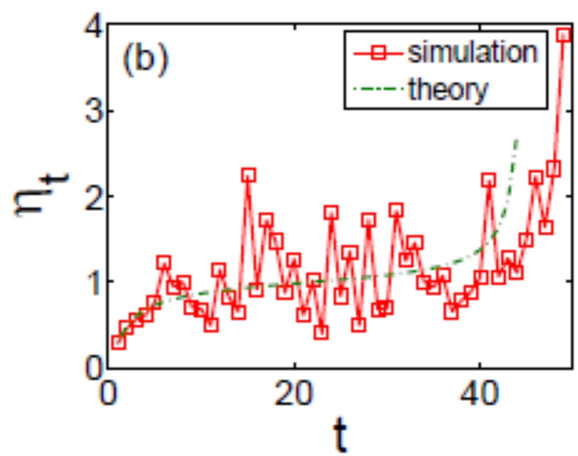
Origin of Plateau

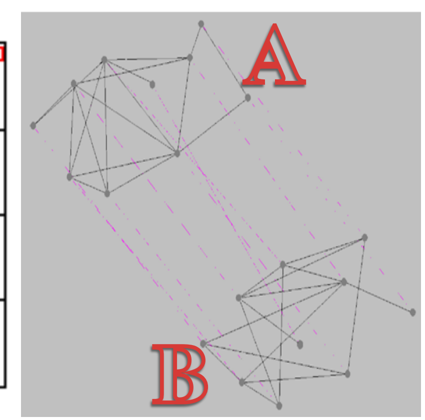
Simultaneous first and second order percolation transitions



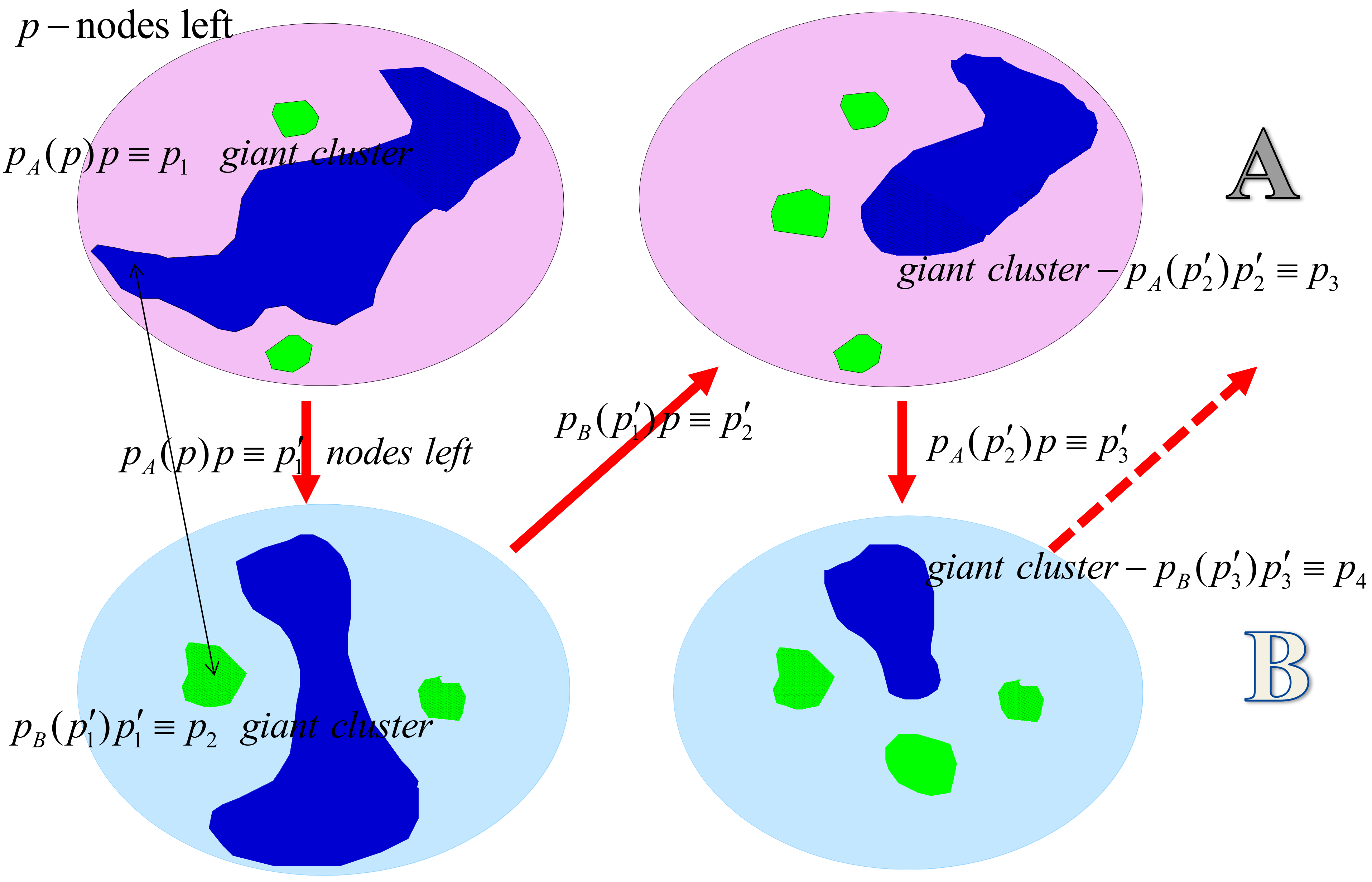
Dong et al,
arXiv:1211.2330
PRE (2014)





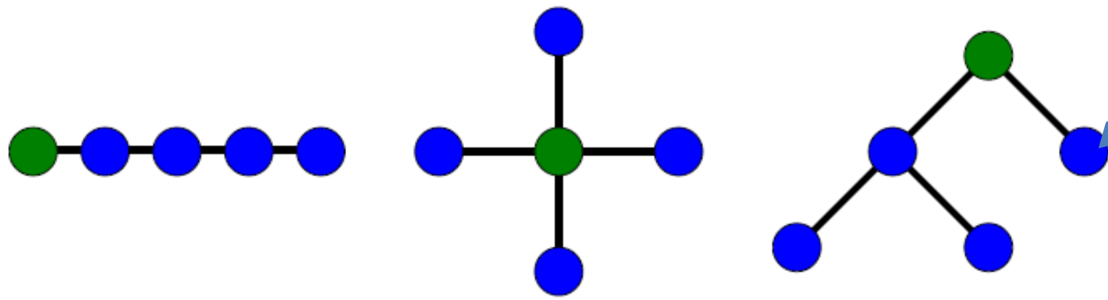


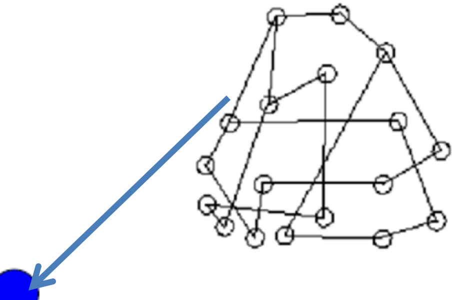
RANDOM REMOVAL – PERCOLATION FRAMEWORK



Network of Networks (tree)

n=5





For ER, $\langle k_i \rangle = k$, full coupling q=1,

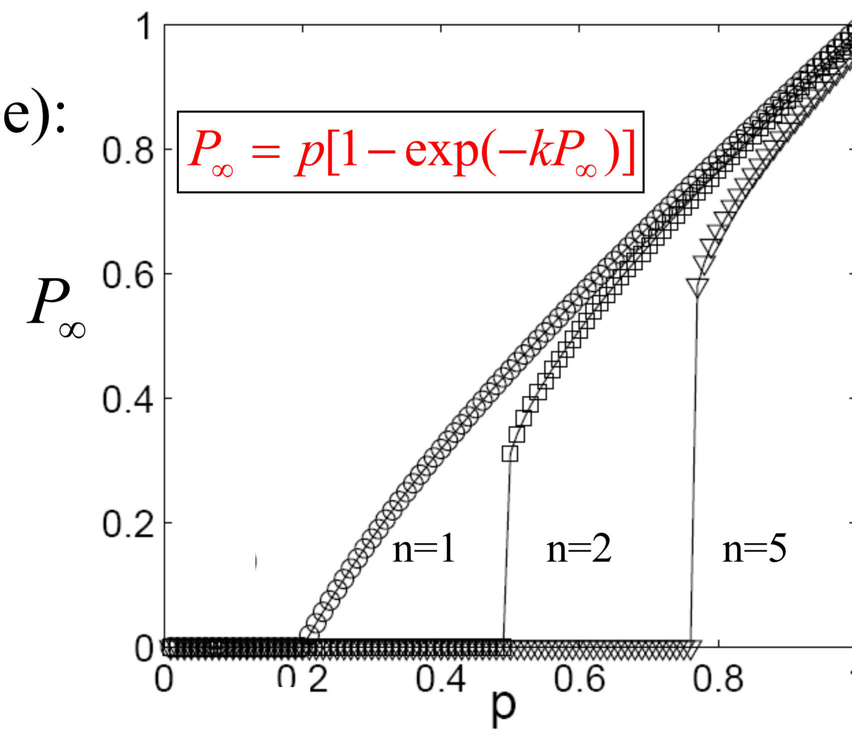
ALL loopless topologies (chain, star, tree):

$$P_\infty = p[1 - \exp(-kP_\infty)]^n$$

n=1 known ER- 2nd order

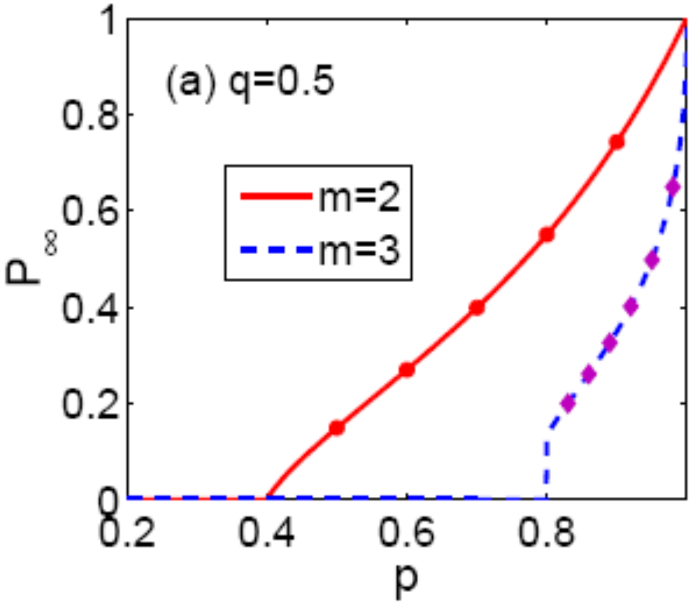
$$p_c = 1/\langle k \rangle$$

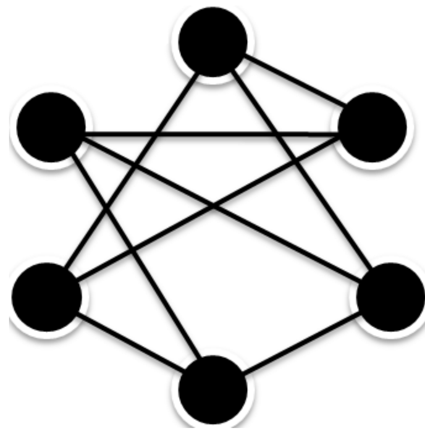
Vulnerability increases significantly with n



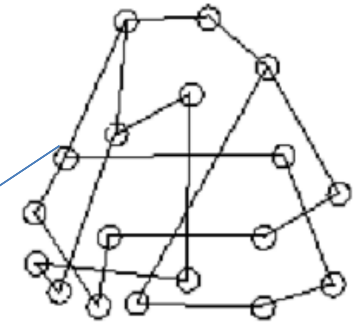
Buldyrev et al, Nature, 464, 1025 (2010)
Parshani et al, PRL ,105, 0484 (2010)
Parshani et al, PNAS, 108, 1007 (2011)
Gao et al PRL (2011)

Random Regular Network of ER networks





RR, m=3



ER $\langle k \rangle = 2.2$

$$P_\infty = \frac{p}{2^m}(1 - e^{-\langle k \rangle P_\infty})[1 - q + \sqrt{(1-q)^2 + 4qP_\infty}\,]^m$$

$$p_c = \frac{1}{\langle k \rangle (1-q)^m}$$

$$q_c = \frac{\langle k \rangle + m - \sqrt{m^2 + 2\langle k \rangle m}}{\langle k \rangle}$$

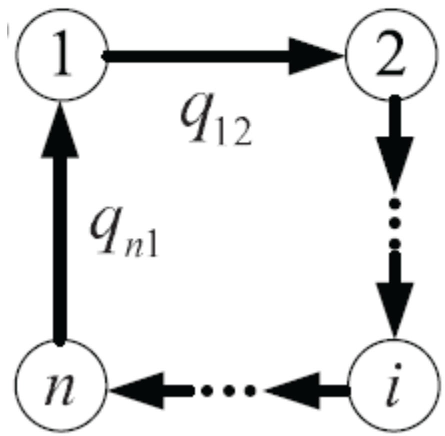
Surprisingly Independent on n!

For $m = 0$ OR $q = 0$ the single network is obtained!

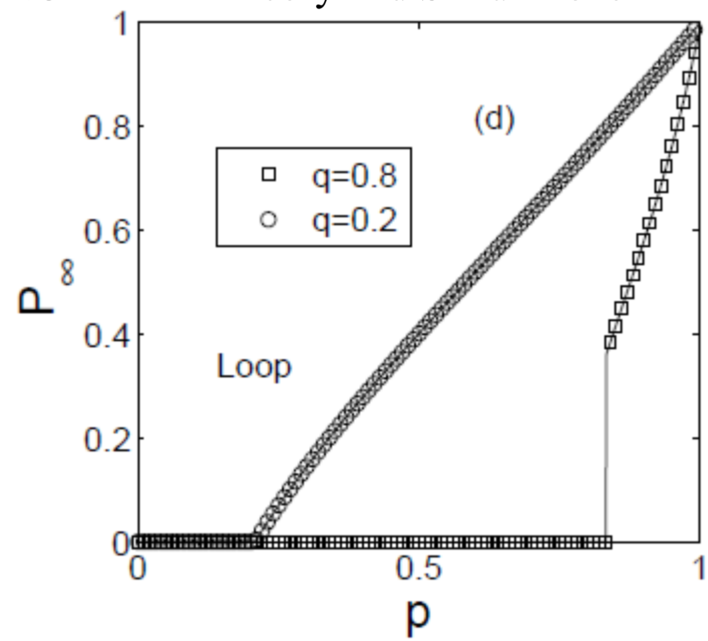
$$P_\infty = p[1 - \exp(-\langle k \rangle P_\infty)]$$

Network of Networks (loop)

GENERAL FRAMEWORK -- PARTIAL DEPENDENCE



Theory and Simulations



For ER networks:

$$P_\infty = p[1-\exp(-kP_\infty)(qP_\infty - q + 1)]$$

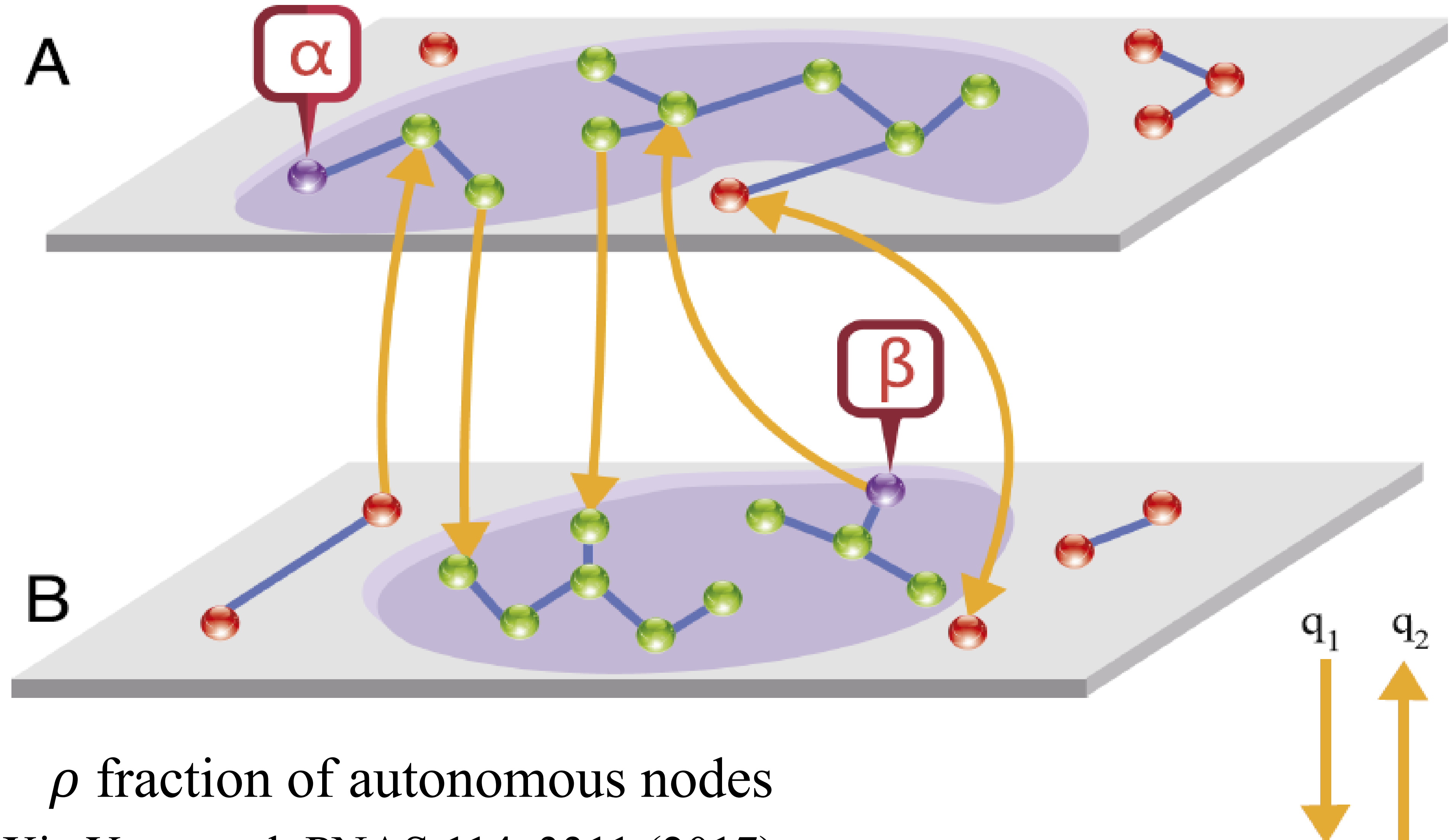
No dependence on m

For $q=1$, $P_\infty = 0$ -no giant component for any p

For $q=0$, the known single network result

Jianxi Gao et al, PRL (2011)

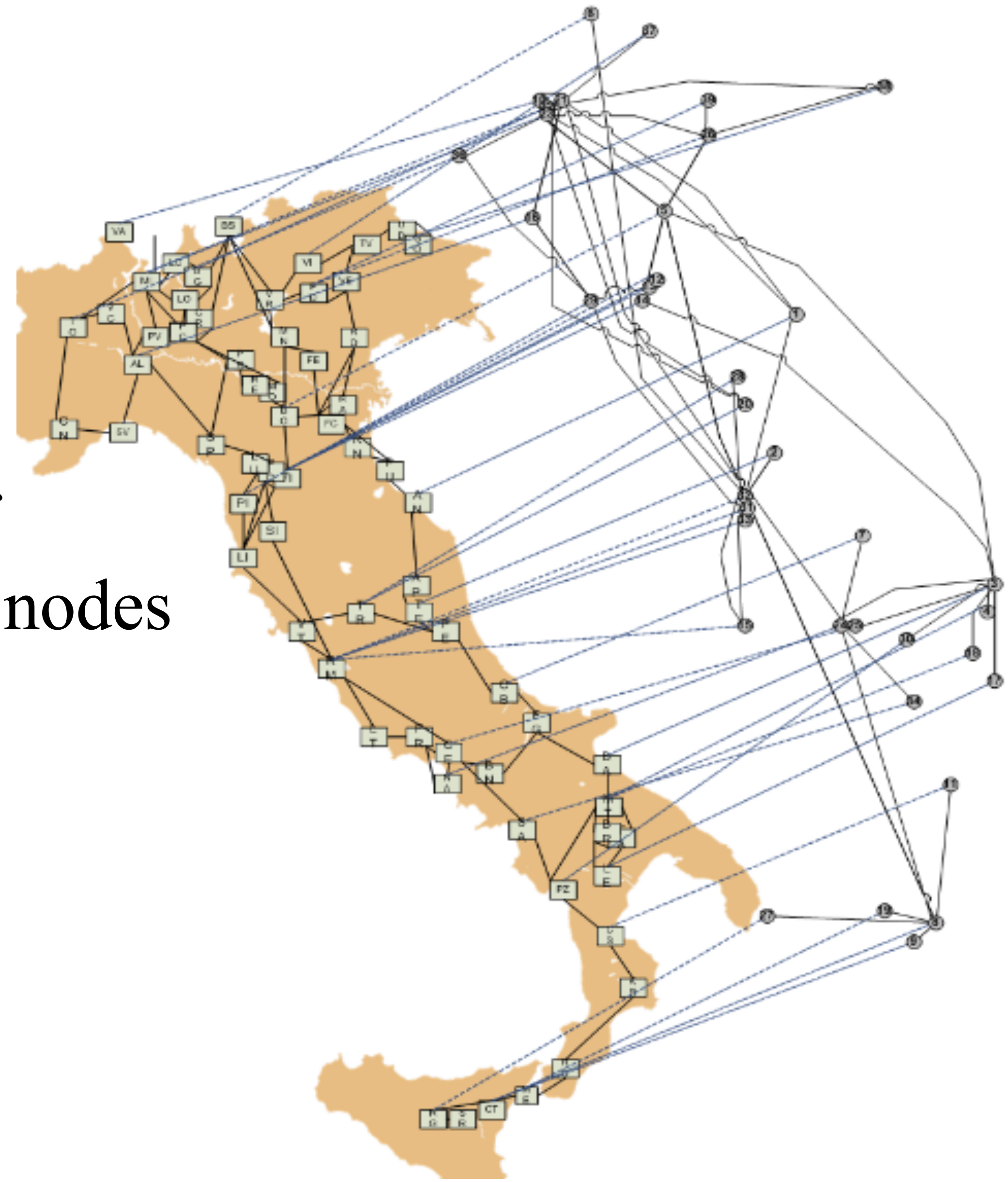
Eradicating abrupt collapse in interdependent networks via reinforced nodes



ρ fraction of autonomous nodes

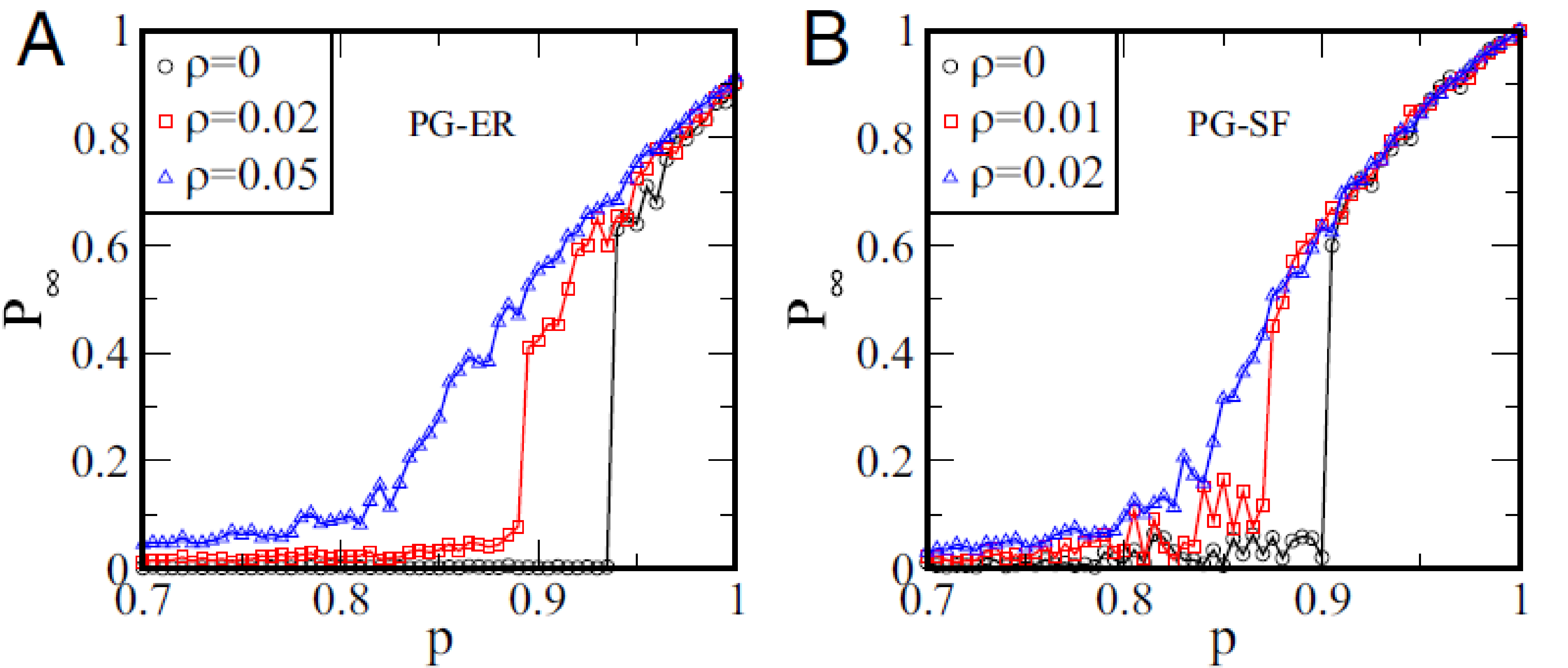
Xin Yuan et al, PNAS **114**, 3311 (2017)

Eradicating catastrophic collapse in interdependent networks via reinforced nodes



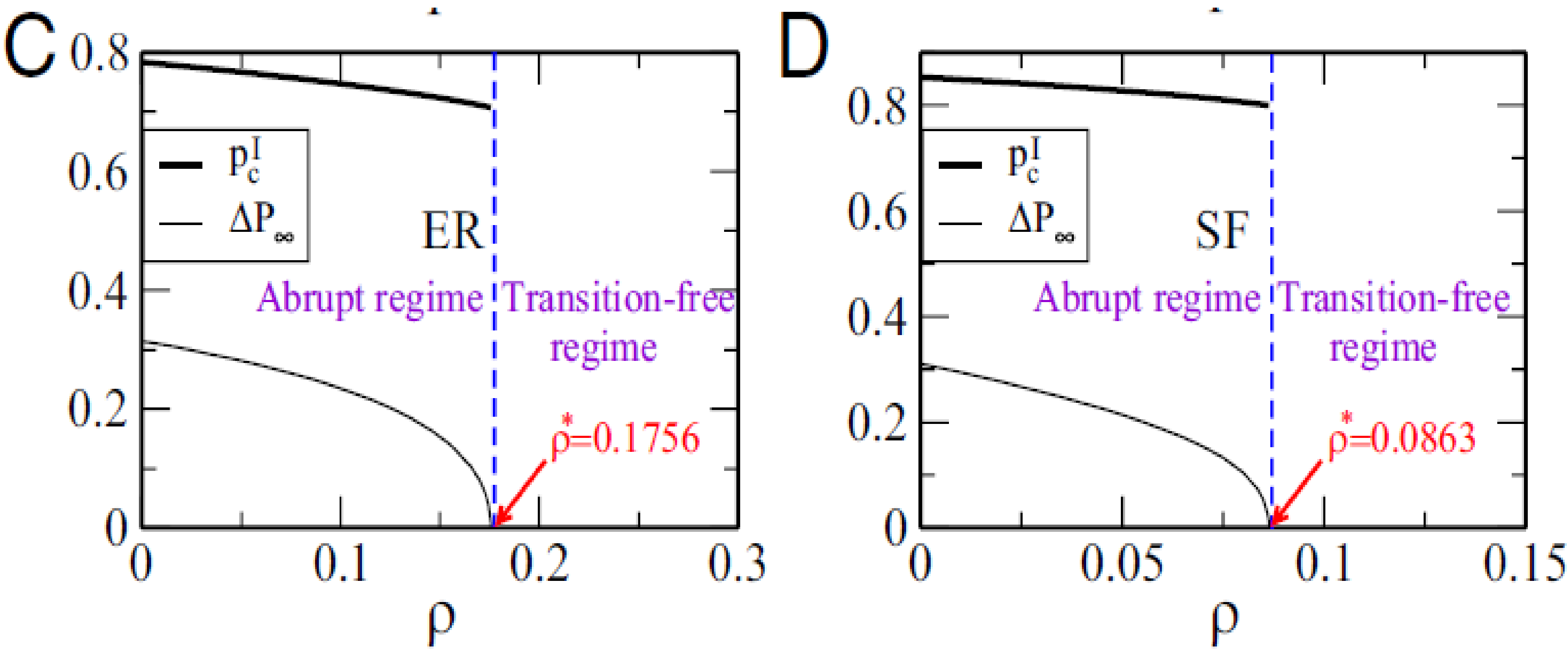
ρ fraction of autonomous nodes

Eradicating catastrophic collapse in interdependent networks via reinforced nodes- Real Data--- US Power grid



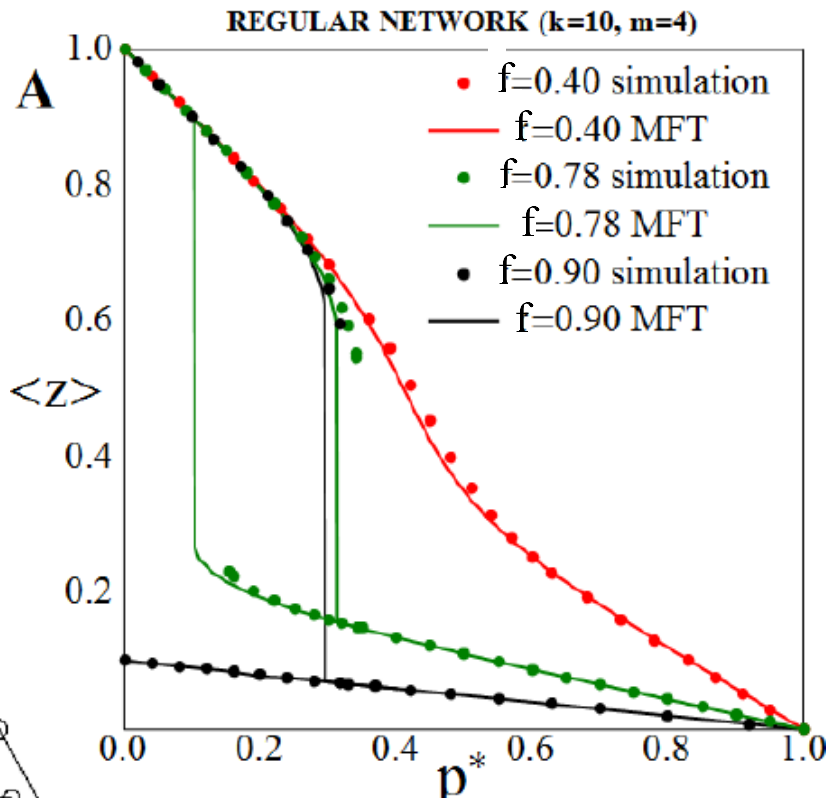
Few percent of autonomous power stations and communication systems can avoid abrupt collapse

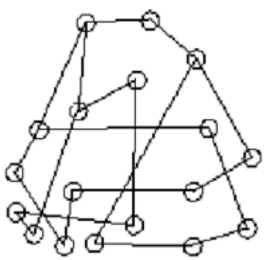
Eradicating catastrophic collapse in interdependent networks via reinforced nodes

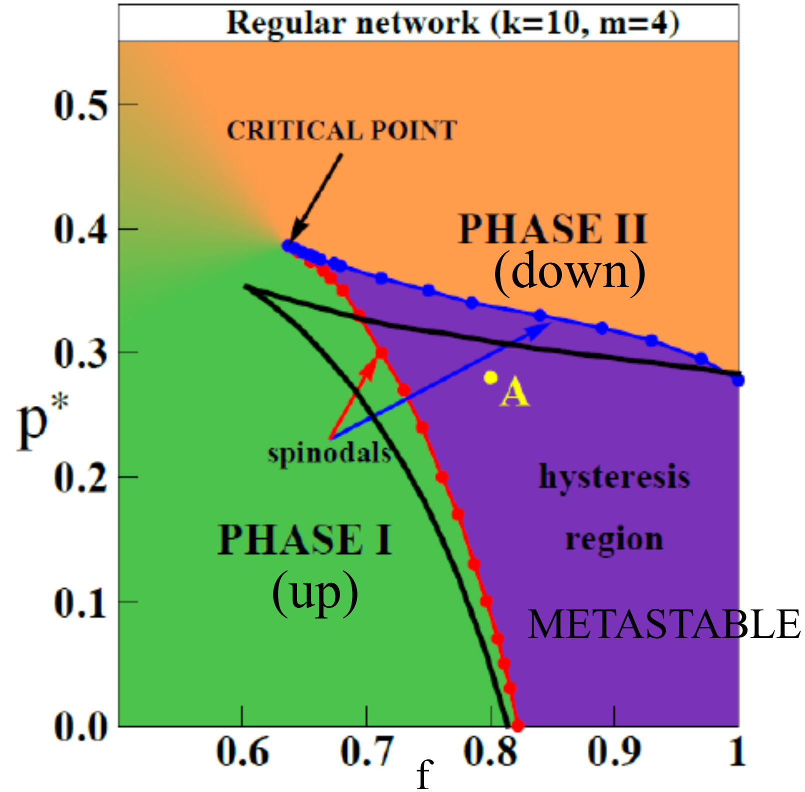


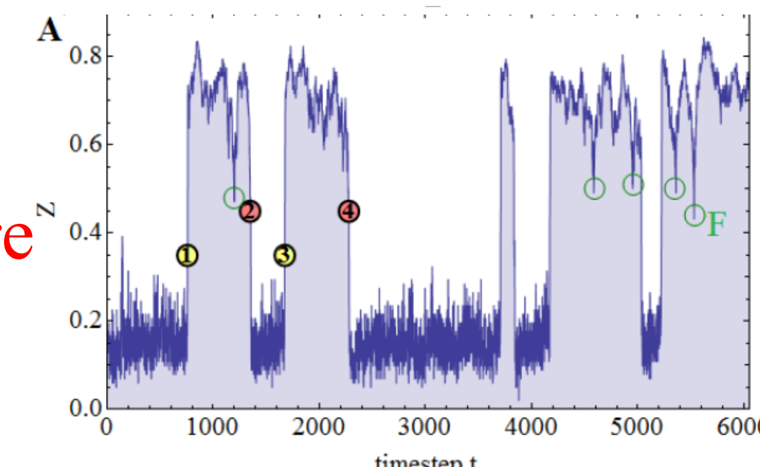
$$\rho^* = 1 - \frac{exp\left\{\frac{1}{2}\left[1 - \langle k \rangle (1-q)^2/2q\right]\right\}}{2 - \sqrt{\langle k \rangle (1-q)^2/2q}}$$

Introducing Recovery-Single Networks





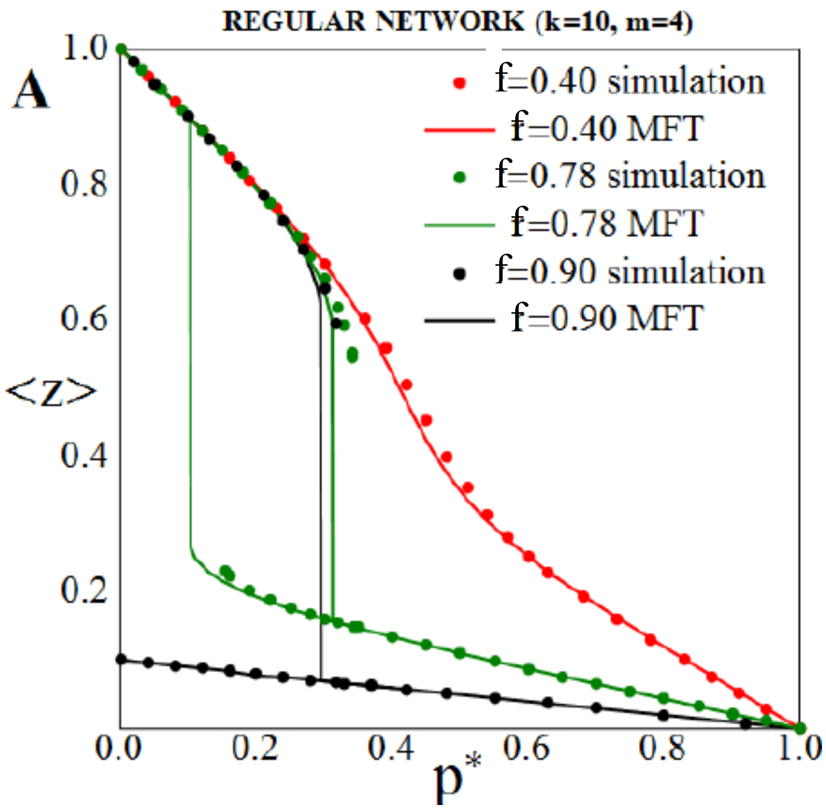


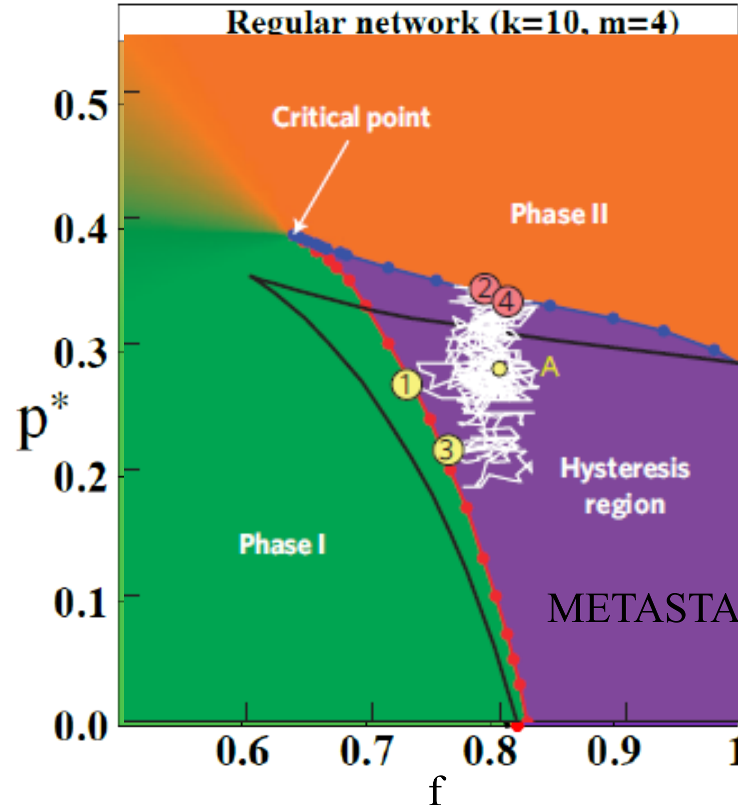


Spontaneous Recovery and Failure

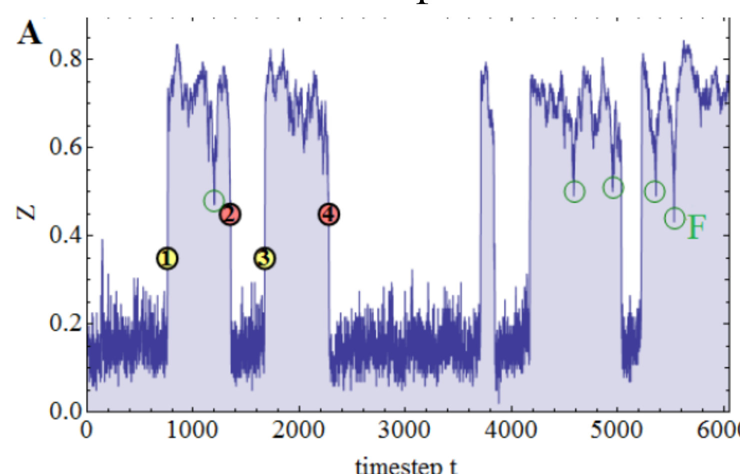
Majdanzik et al Nature Phys. 10, 3438 (2014)

Introducing Recovery-Single Networks





METASTABLE

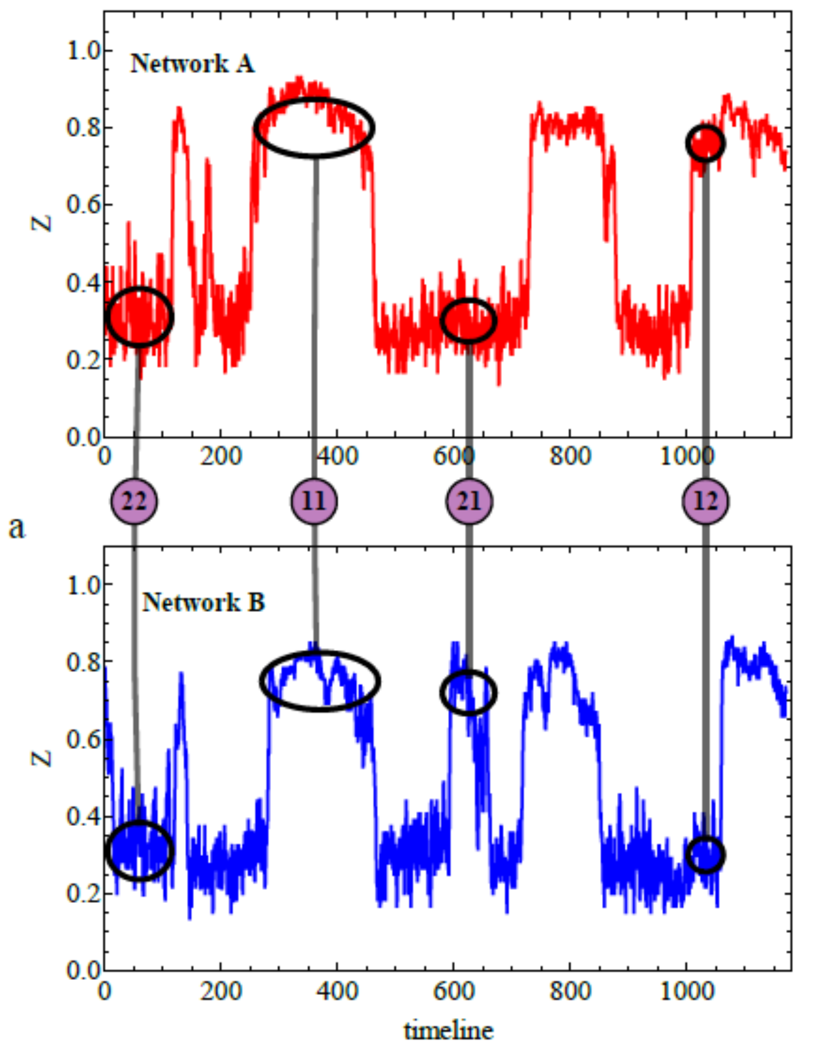


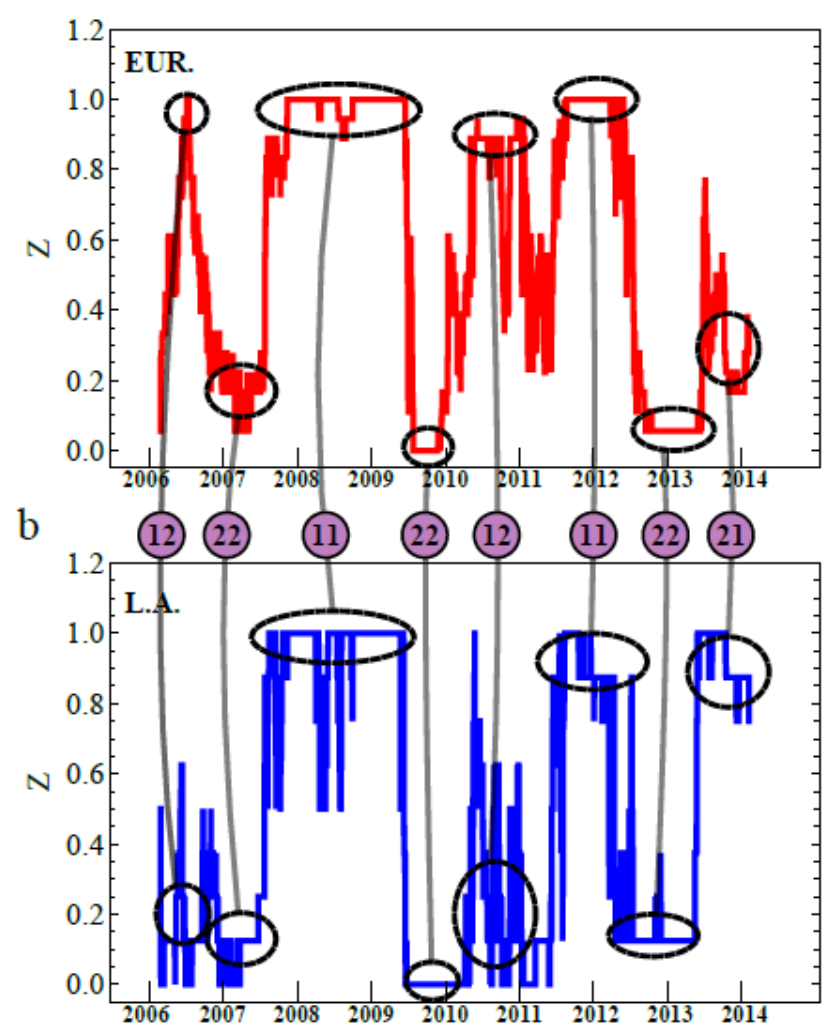
Diffusion of a SYSTEM in phase space

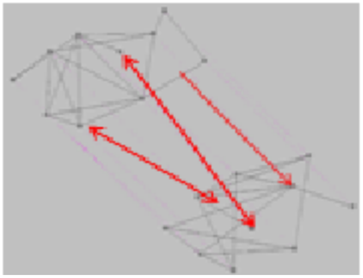
Spontaneous Recovery and Failure

Majdanzik et al Nature Phys. 10, 3438 (2014)

Simultaneous Recovery and Failure of Interdependent Networks



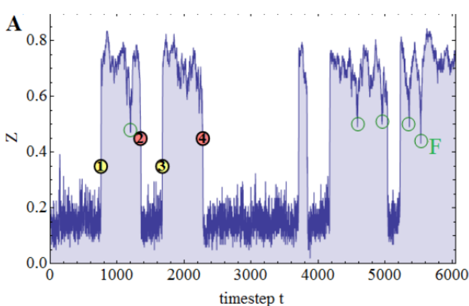




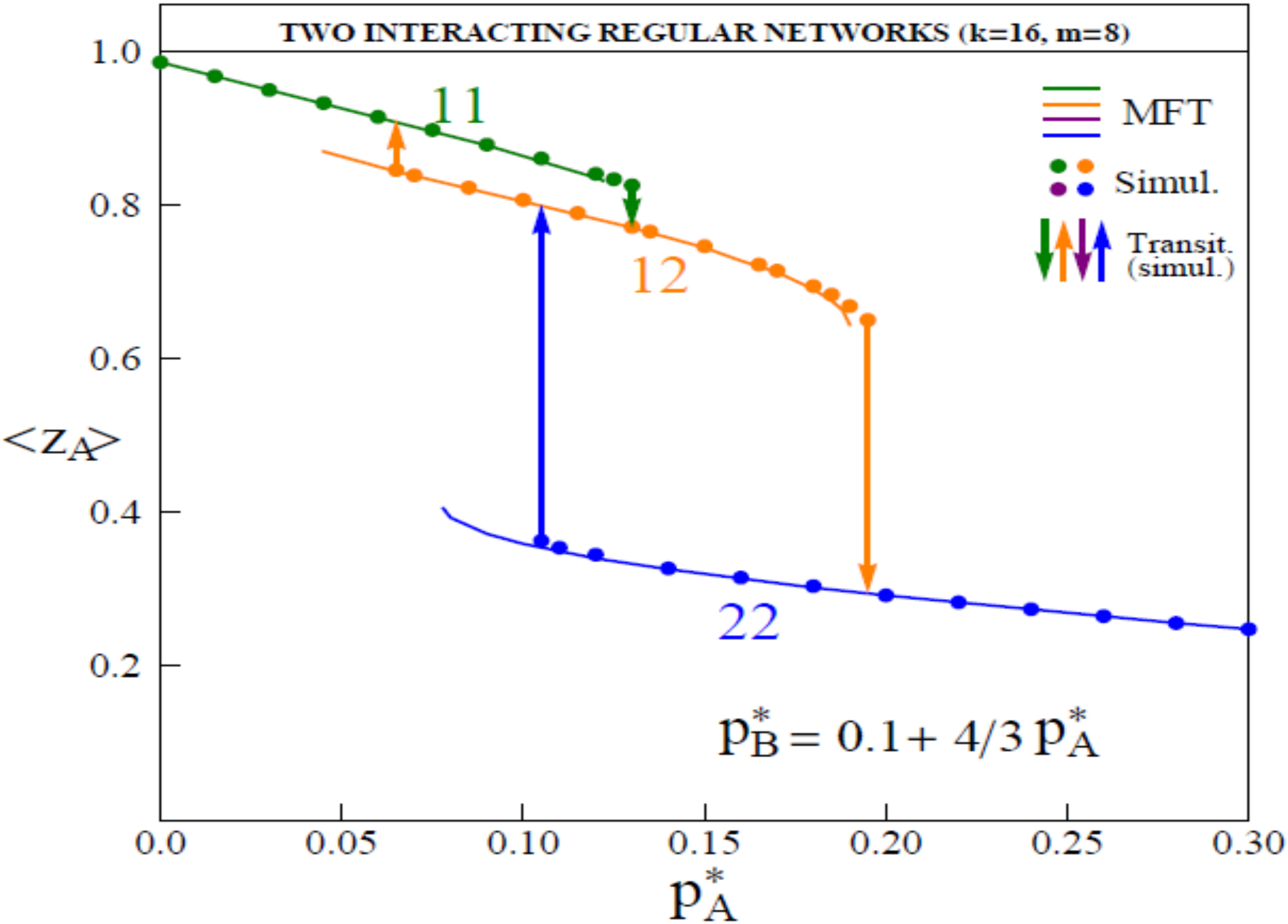
CDS INDEX DATA FROM EUROPE AND LATIN AMERICA

Majdanzic et al

Nature Comm. **7**, 10850 (2016)

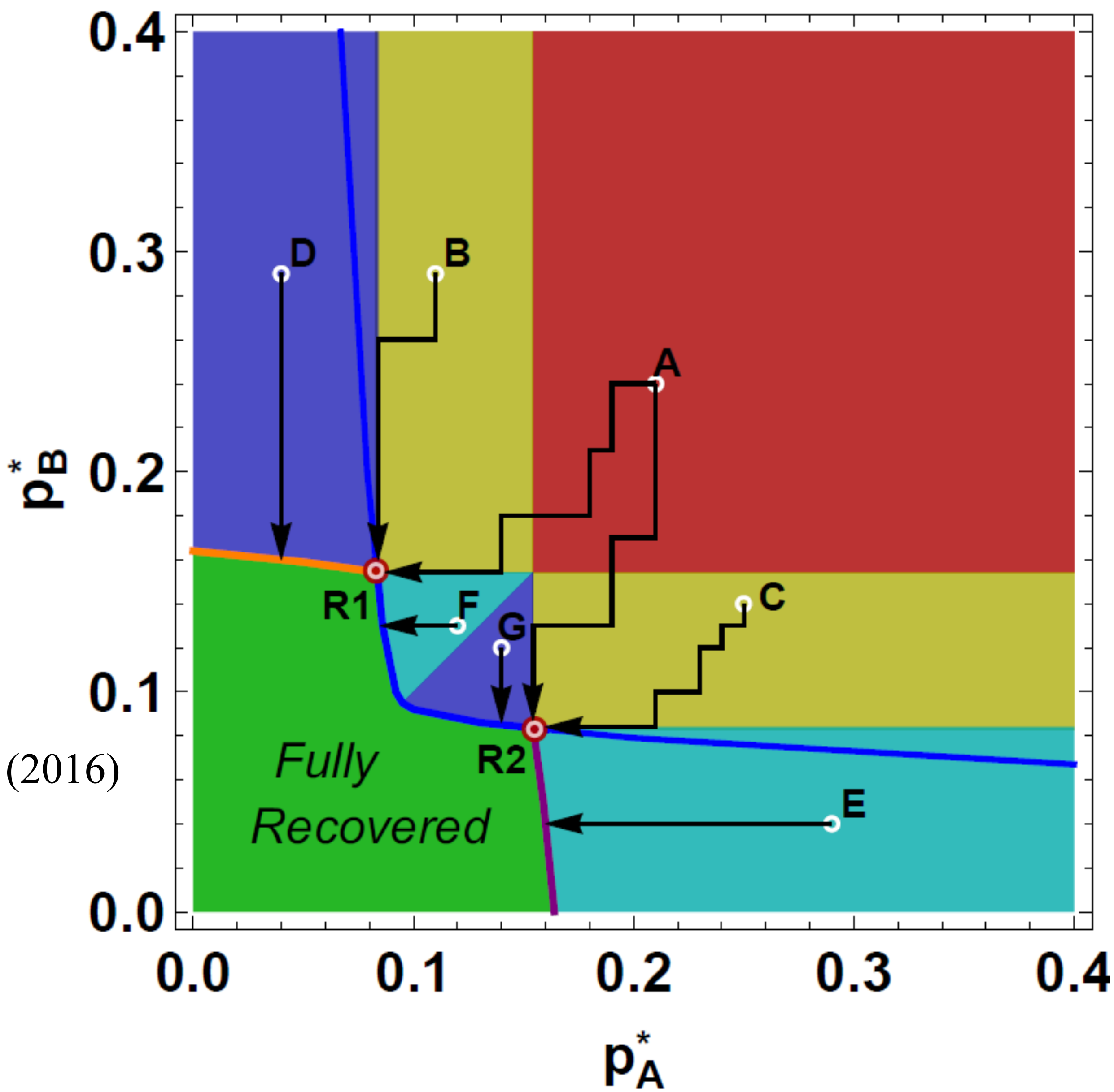


Complex Hysteresis-Interdependent Networks



Majdanzic et al Nature Comm. **7**, 10850 (2016)

Optimal Repairing Strategies



Majdanzic et al

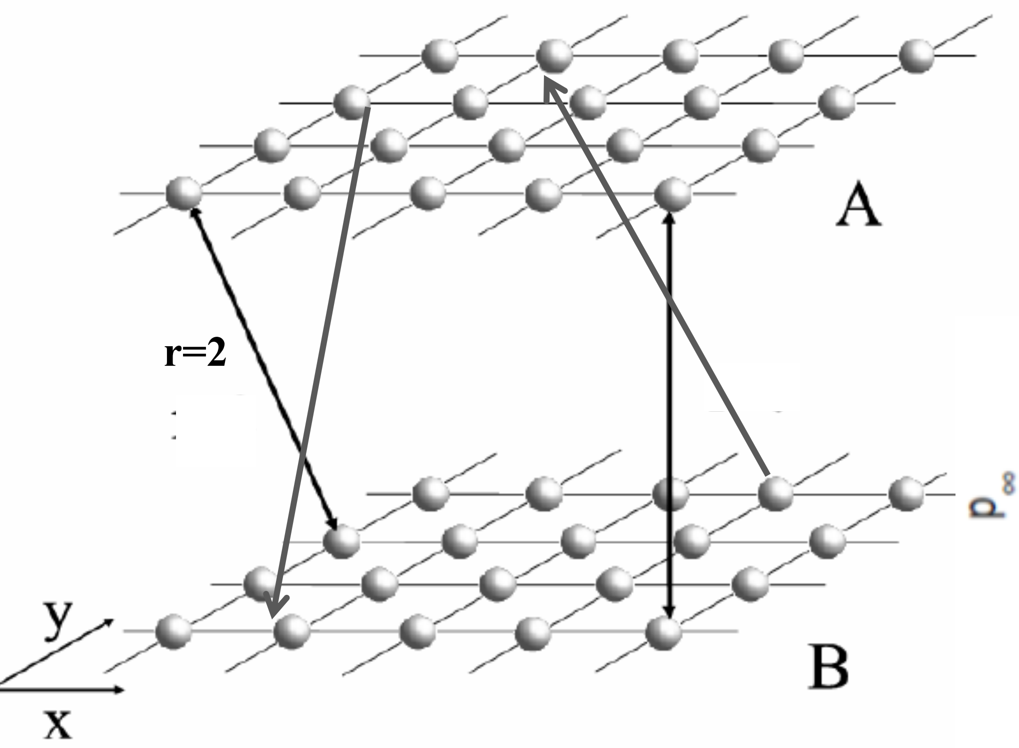
Nature Comm. **7**, 10850 (2016)

Infrastructure of many interdependent systems

Species distinction

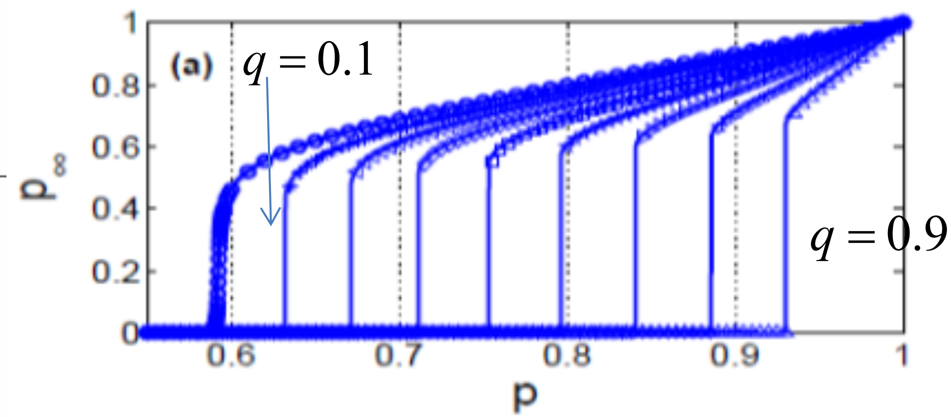
System collapse

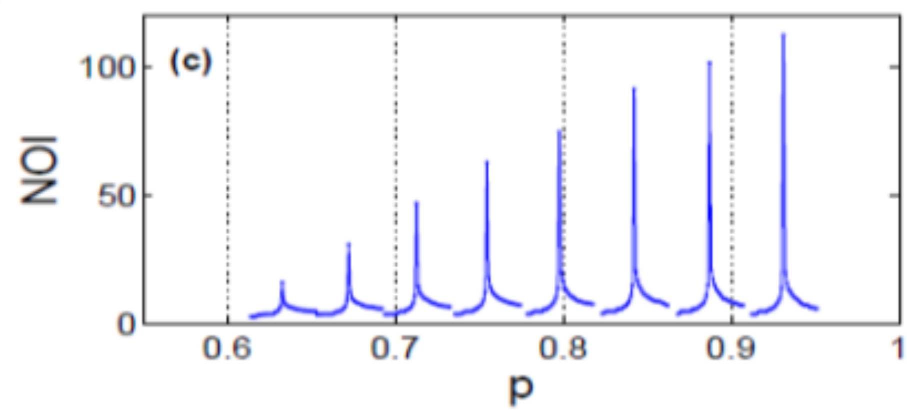
Interdependent Spatially Embedded Networks



Many networks are spatially embedded: Internet, Power grid, Transportation etc

Bashan et al, Nature Physics (2013)

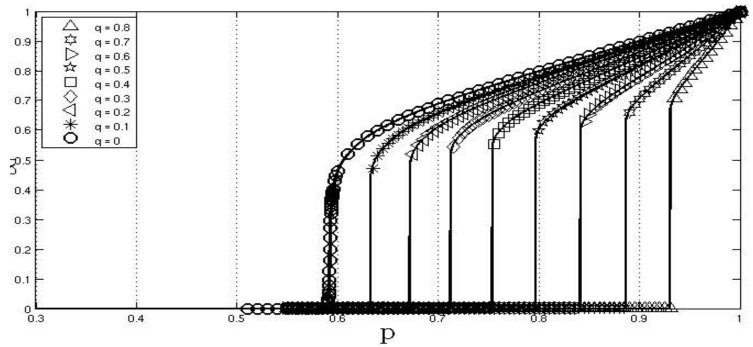




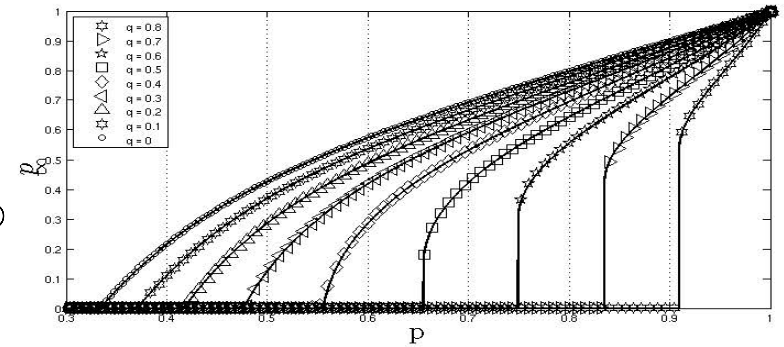
Theory (based on critical exponent):
NO continuous transition
for any q>0-extreme vulnerability!!

The extreme vulnerability of spatial embedded coupled networks

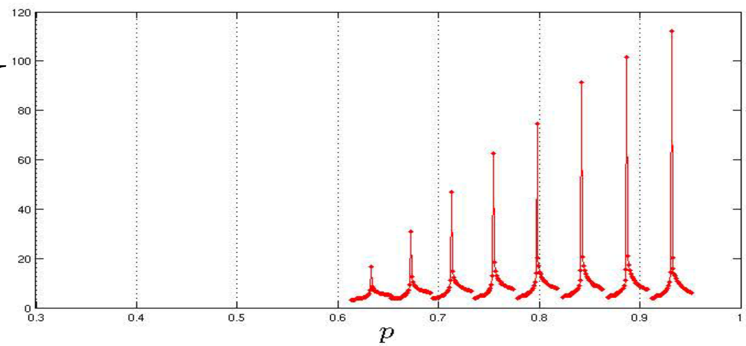
P_∞



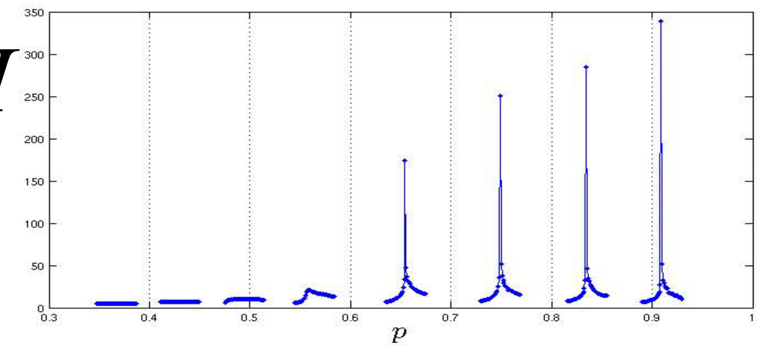
P_∞

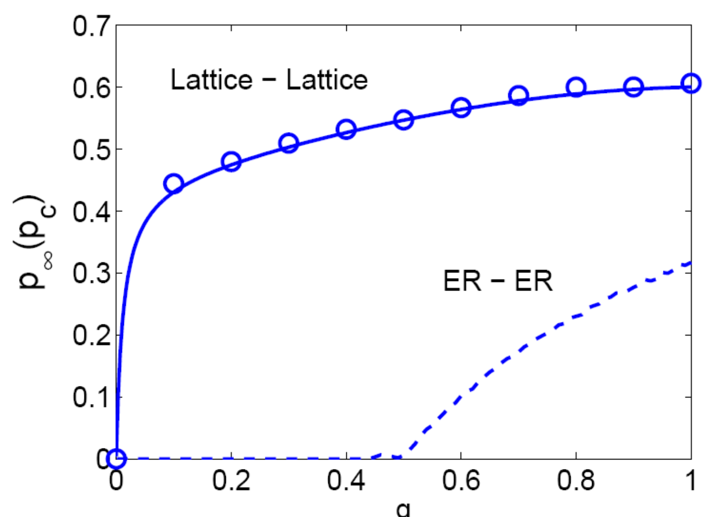


NOI



NOI



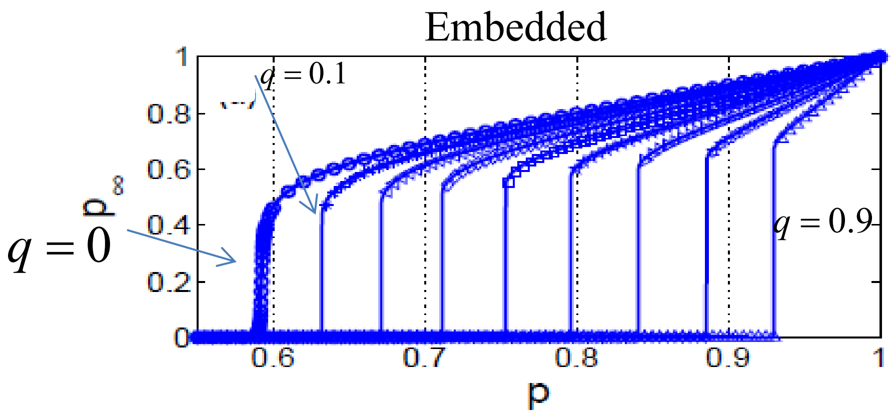


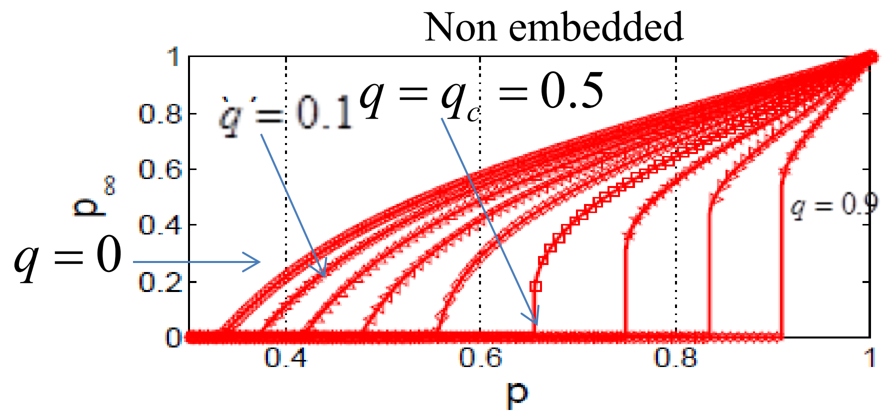
EXTREMELY VULNERABLE!!

Bashan et al
http://arxiv.org/abs/1206.2062

$q_c = 0$

Spatial embedded compared to random coupled networks when q changes





EXTREMELY VULNERABLE!!

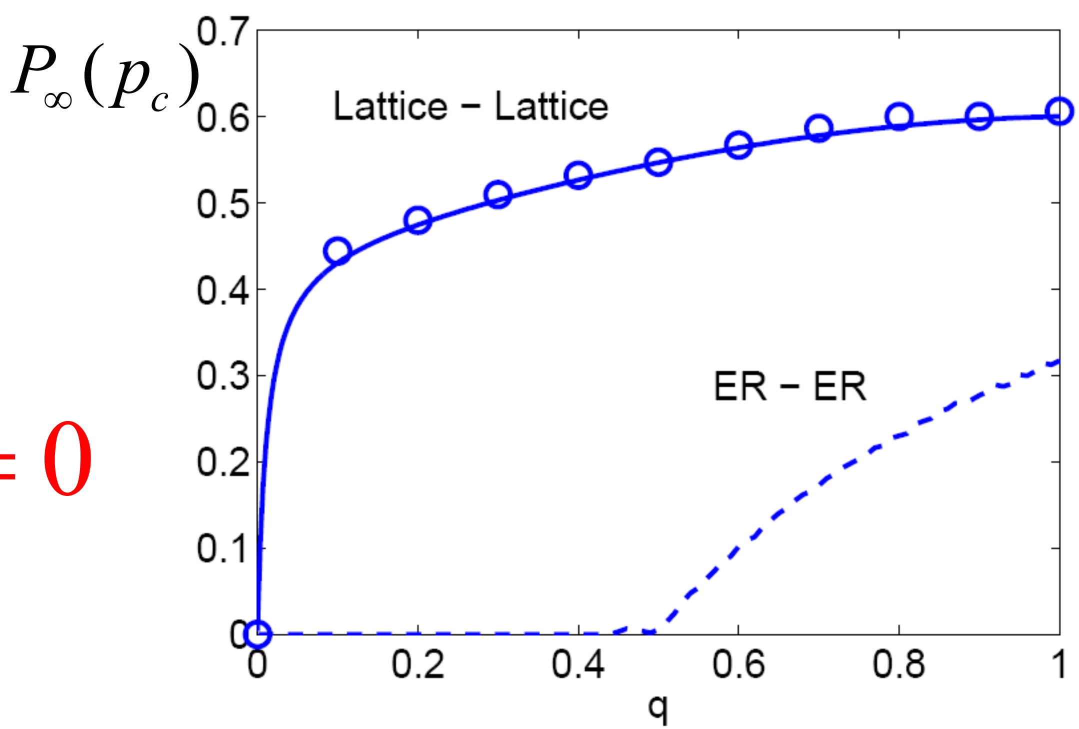
$$1 = p_c q_c P'_\infty(p_c)$$

$P_\infty \sim (p - p_c)^\beta$

$\beta = 5/36 < 1$ for d=2

For ER and d=6, β=1

$$q_c = 0$$



Bashan et al

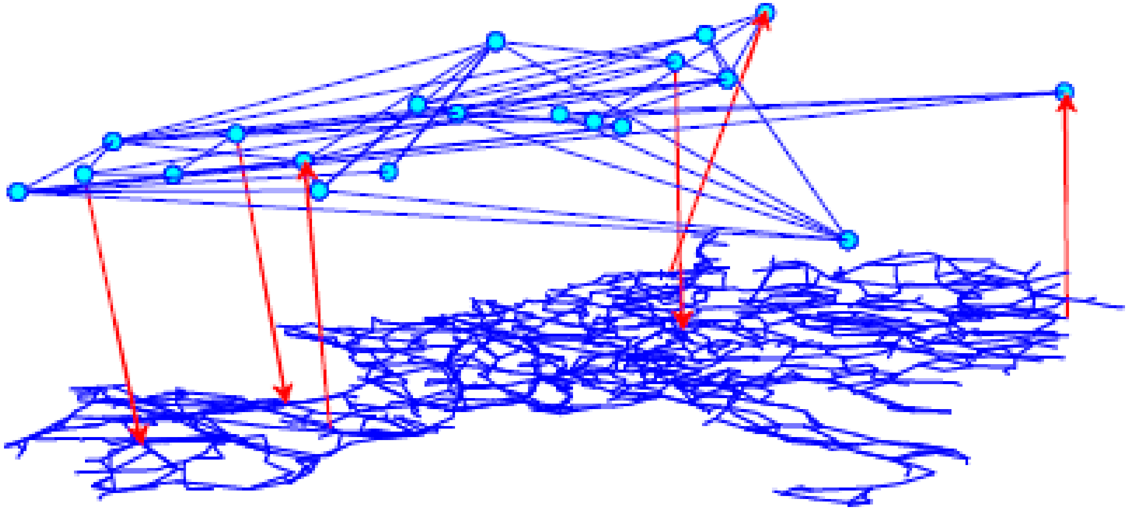
http://arxiv.org/abs/1206.2062

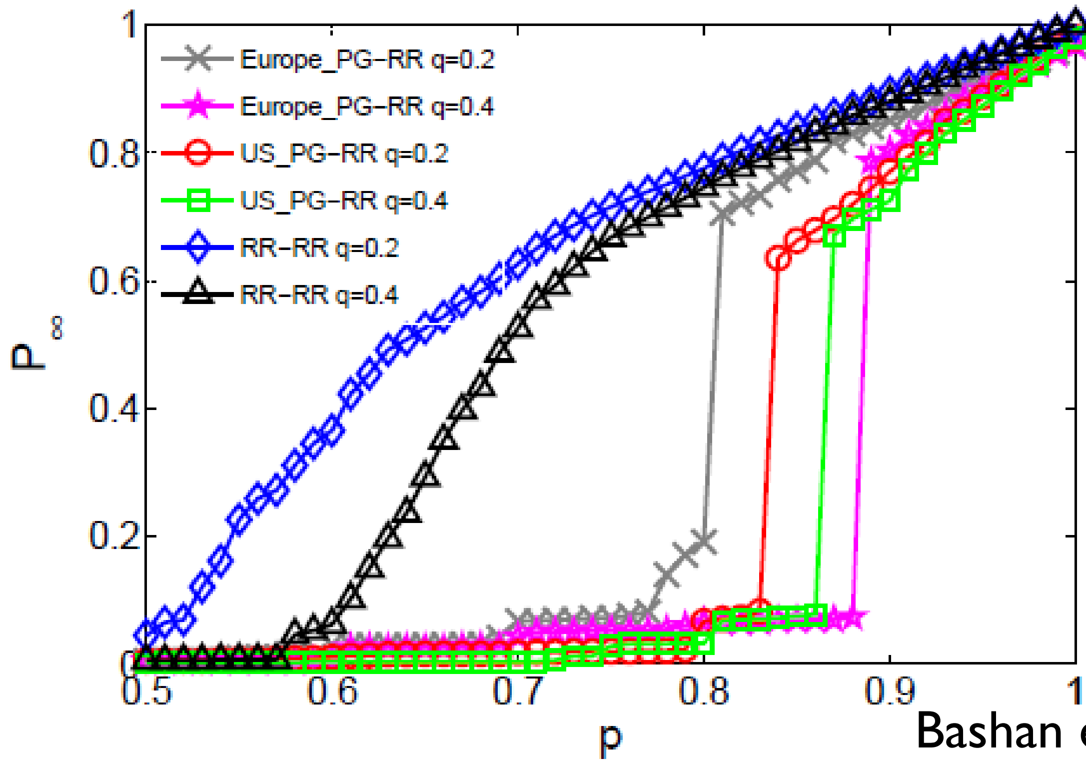
Nature Physics, (2013)

Message: our world is extremely **unsafe!-no safe zone!**

Experimental test on real spatial embedded coupled networks

Interdependent European Communication Network and Power Grid

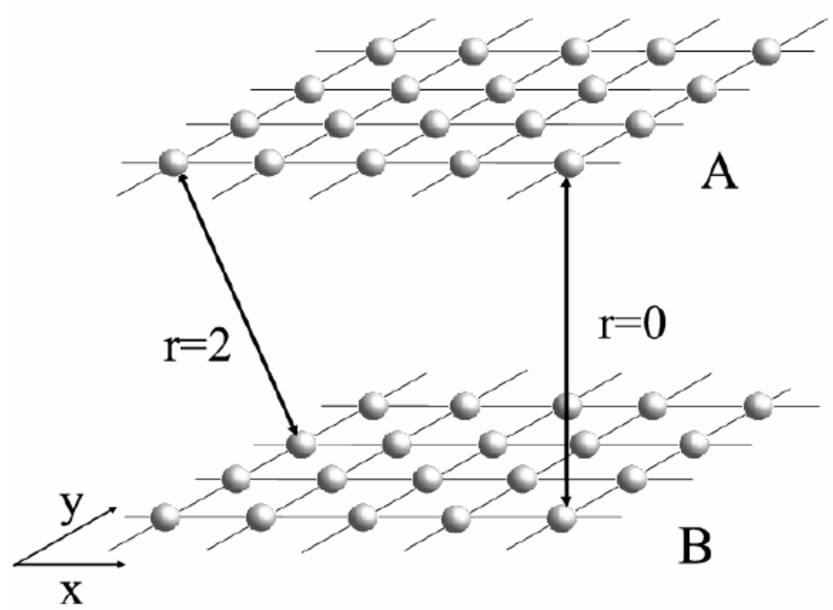




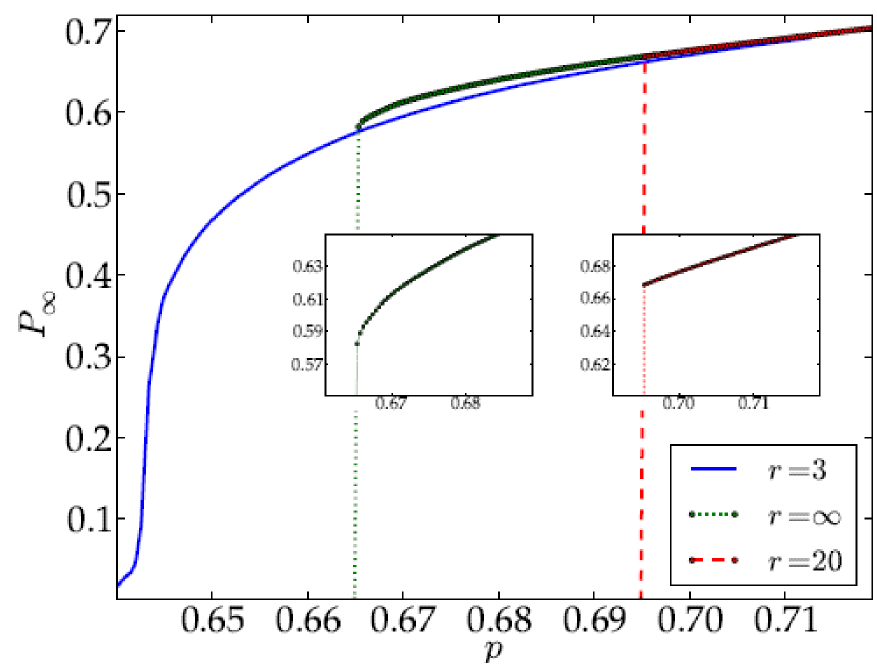
Results for European and US Interdependent Communication Networks and Power Grids

Bashan et al, Nature Physics (2013)

Interdependent Spatially Embedded Networks



Many networks are spatially embedded:
Internet, Power grid, Transportation etc



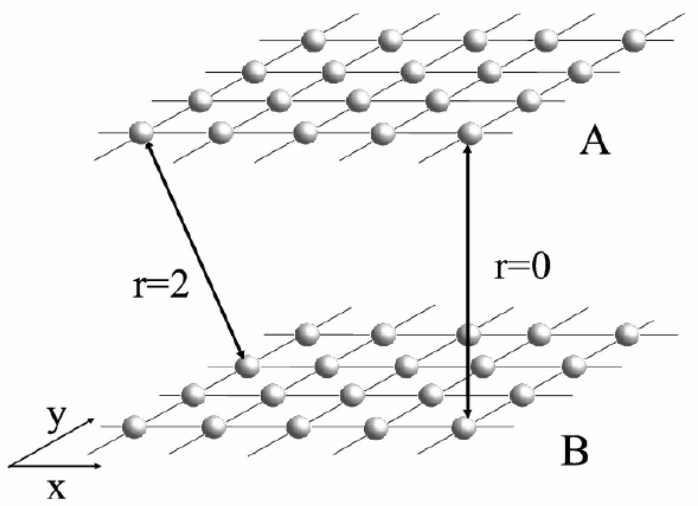
When connectivity links are limited in their length---same universality class as lattices!

THREE DIFFERENT BEHAVIORS
DEPENDING ON r

Wei et al, PRL, 108, 228702 (2012)

Bashan et al, Nature Physics (2013)

Interdependent Spatially Embedded Networks



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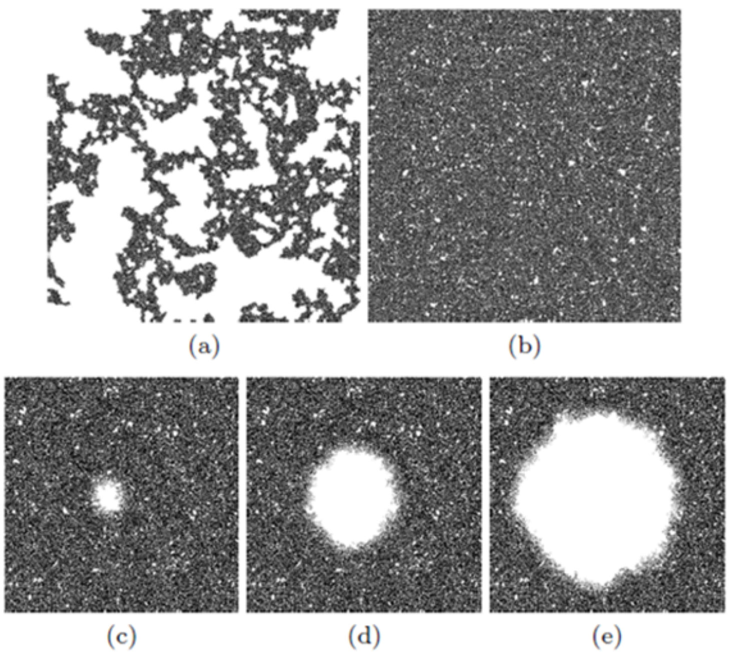
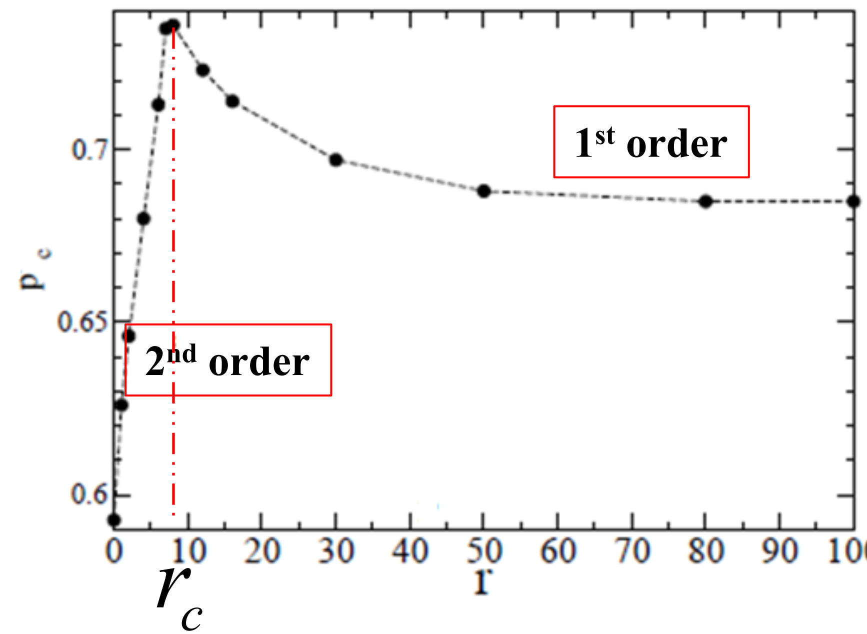
Internet, Power grid, Transportation etc





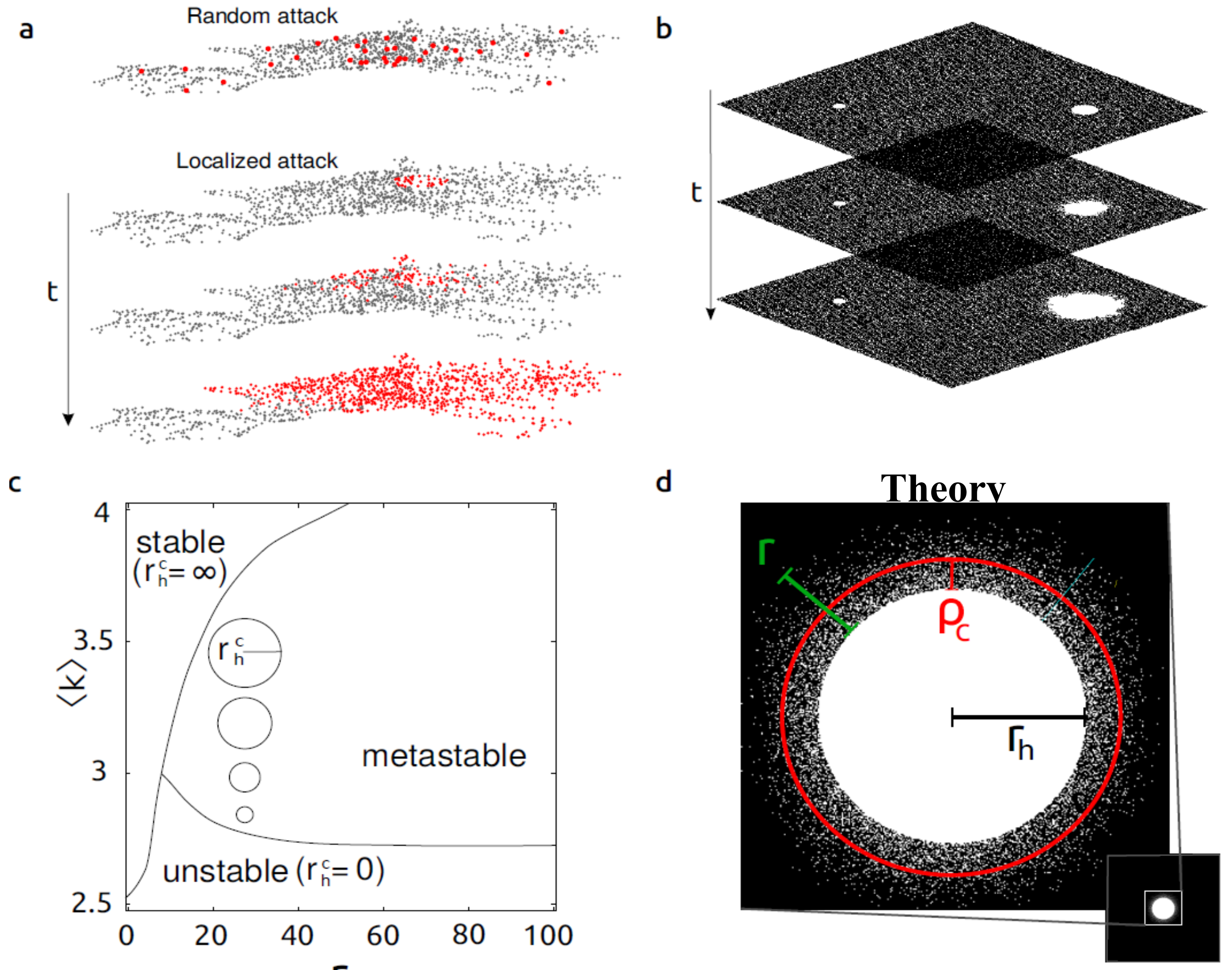
Wei et al, PRL, 108, 228702 (2012)

Bashan et al, http://arxiv.org/abs/1206.2062

New percolation-localized attacks

Localized attacks on spatially embedded systems with dependencies: critical size attack

Y. Berezin et al, .
arXiv:1310.0996



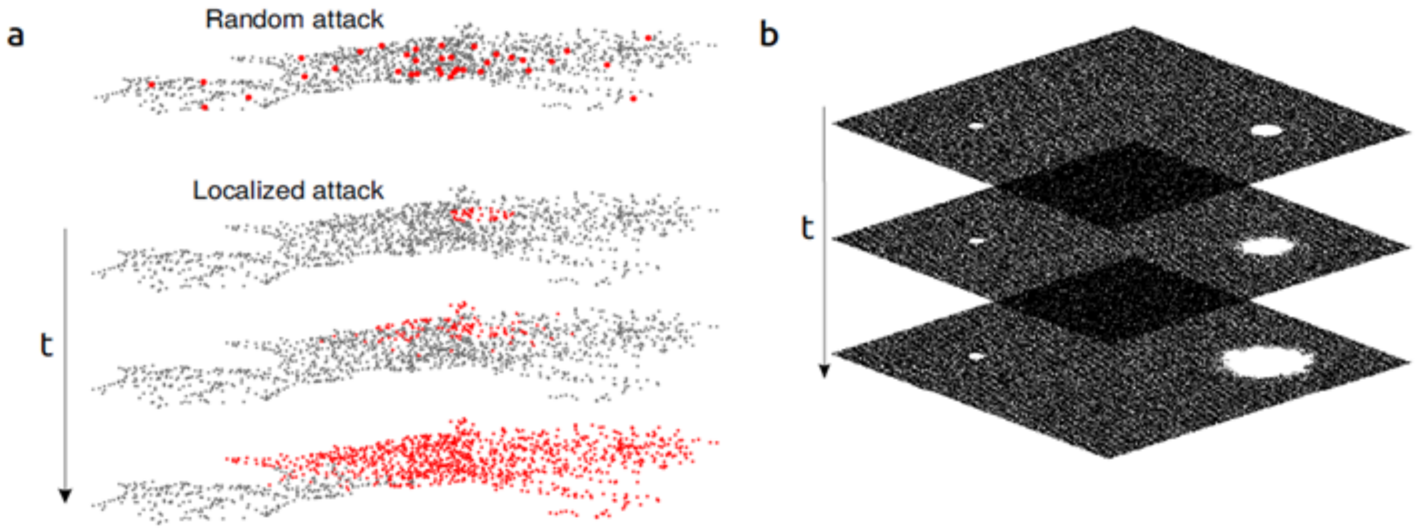
Gradient percolation, Sapoval et al (1985)

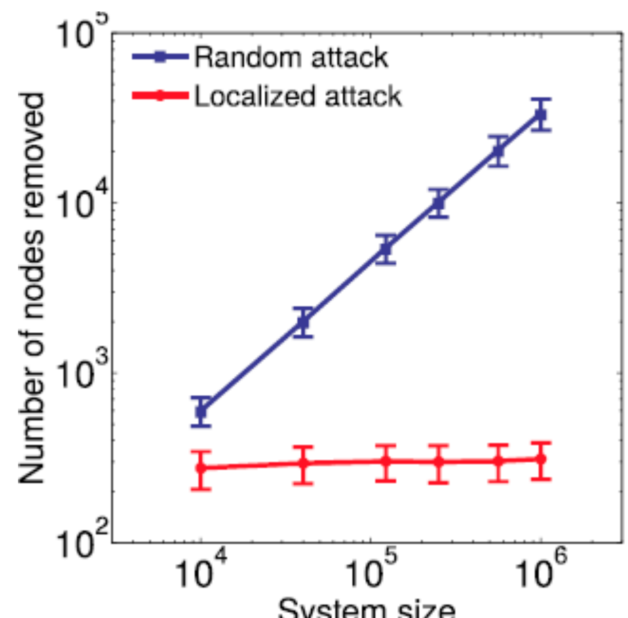
New percolation-localized attacks

Localized attacks on spatially embedded systems with dependencies: critical size attack

Y. Berezin et al, . Scientific Reports (2015)

Europe-power grid



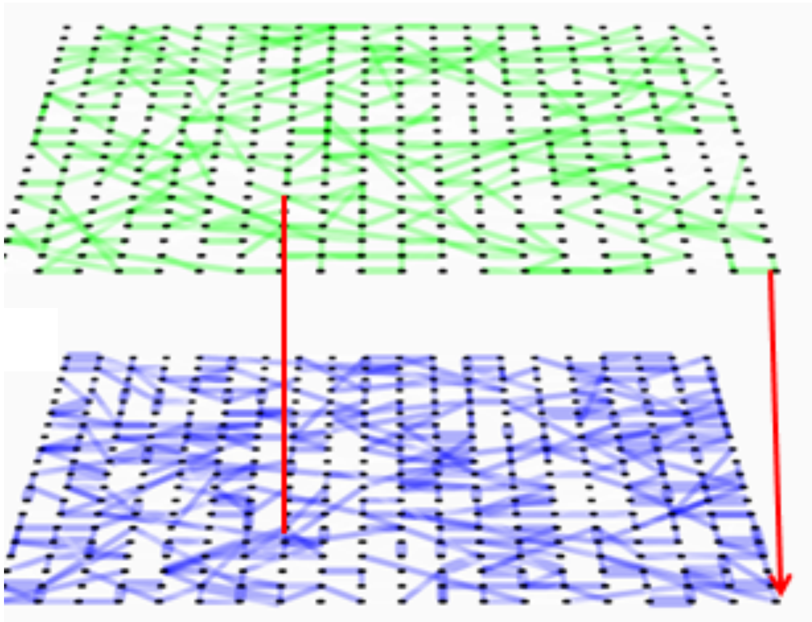


FINITE SIZE FAILURE
CATASTROPHIC COLLAPSE

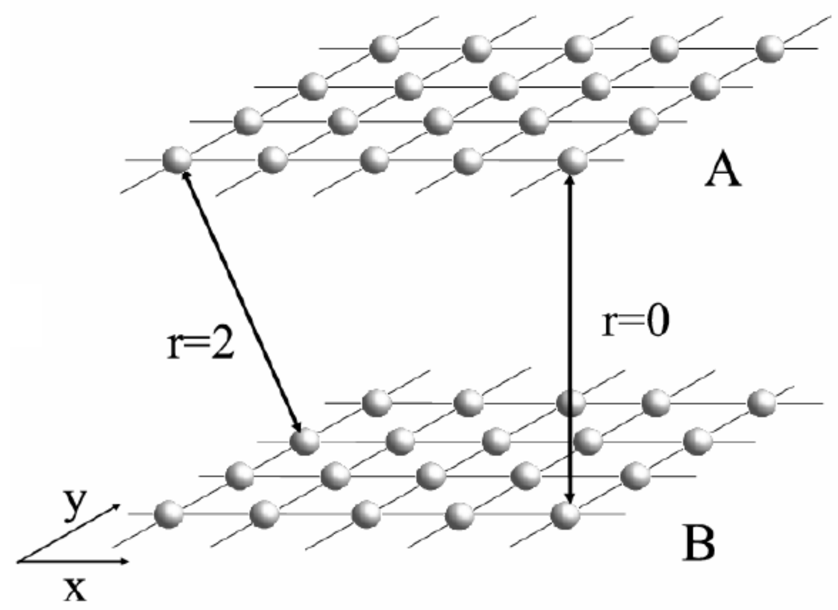
$$p_c = 1$$

Interdependent Spatially Embedded Networks – Two Models

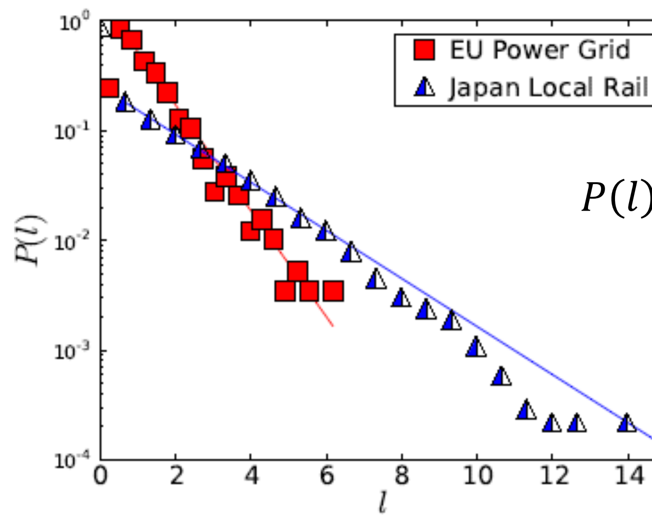
Connectivity Length (Multiplex)



Dependency Length



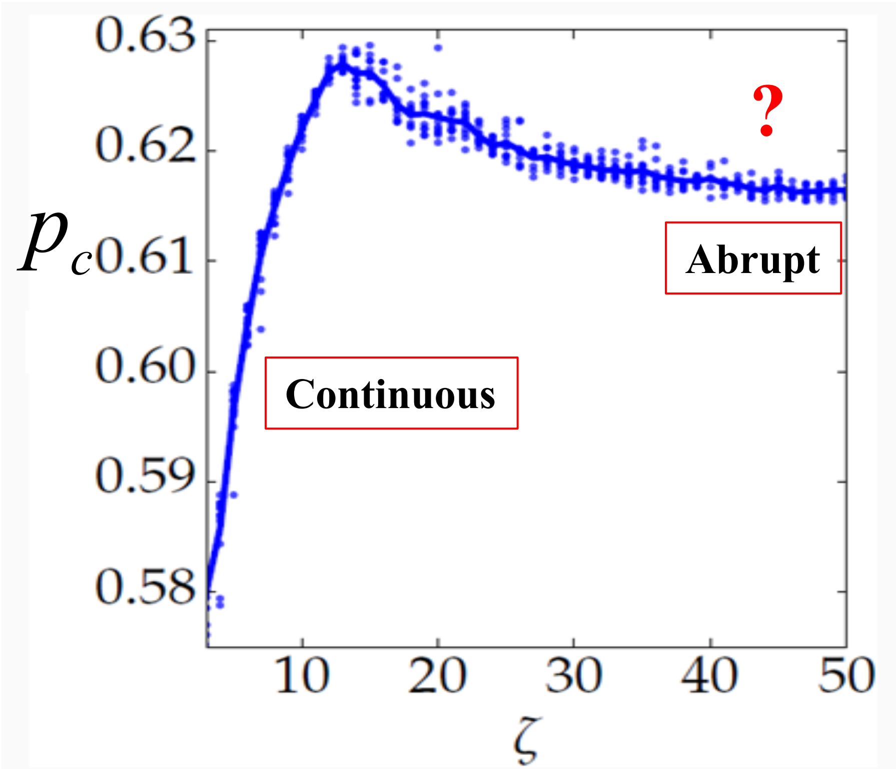
Japan Railway Network



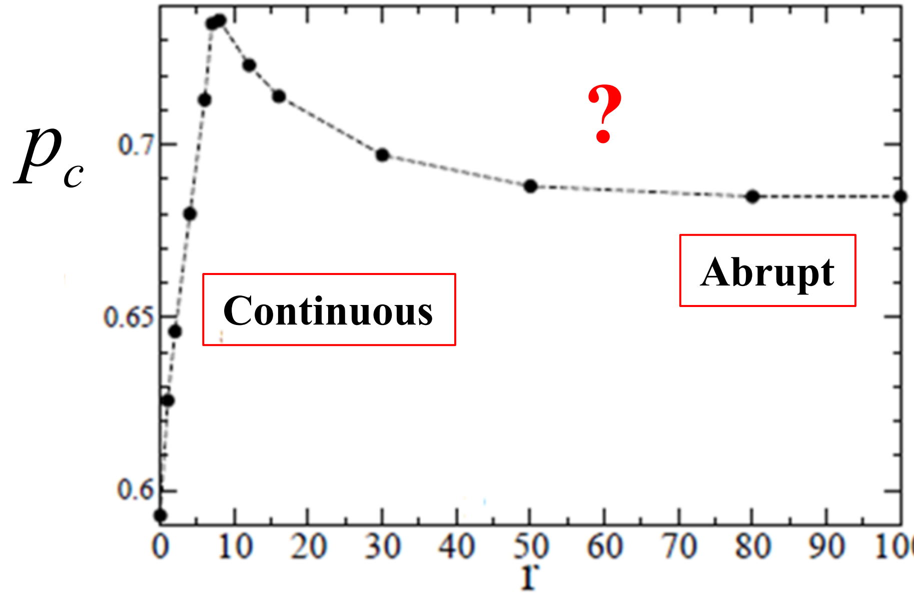
$$P(l) \sim \exp\left(-\frac{l}{\zeta}\right)$$

RANDOM FAILURES-TWO MODELS

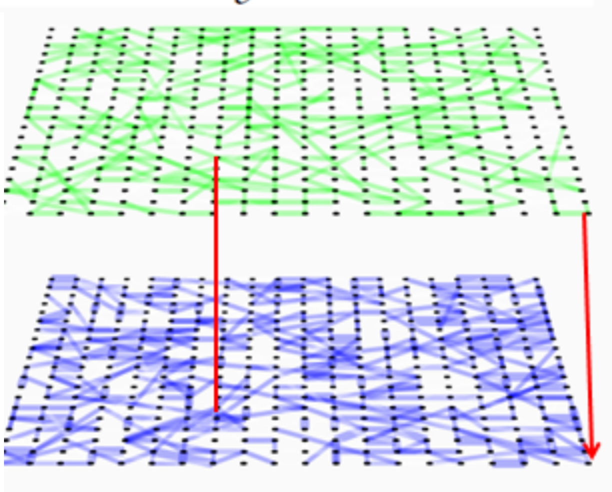
Connectivity Length

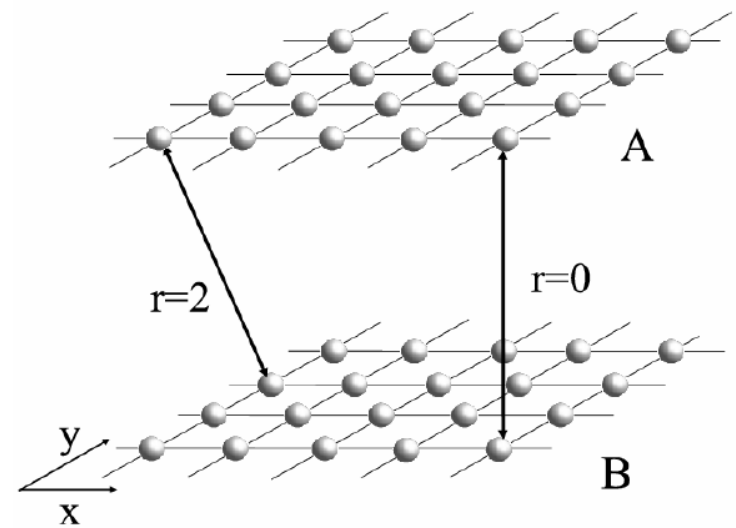


Dependency Length



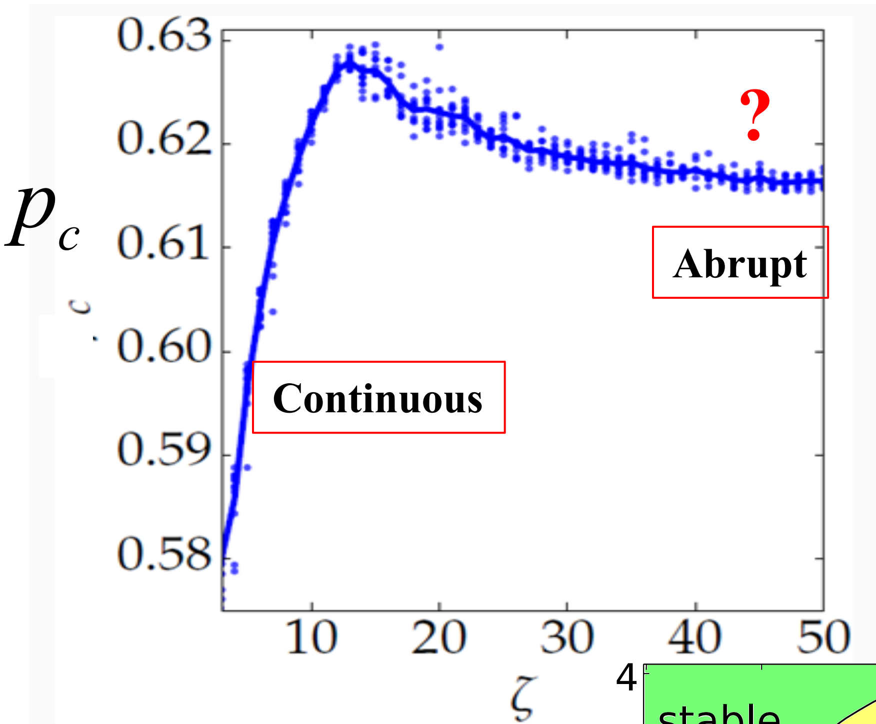
Multiplex
Danziger et al
EPL, 2016
Vaknin et al,
NJP, 2017



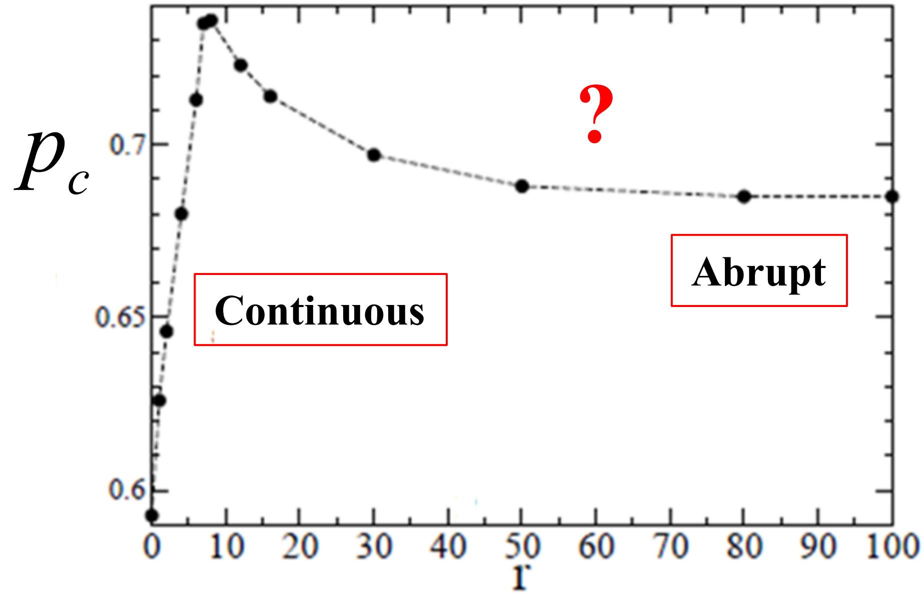


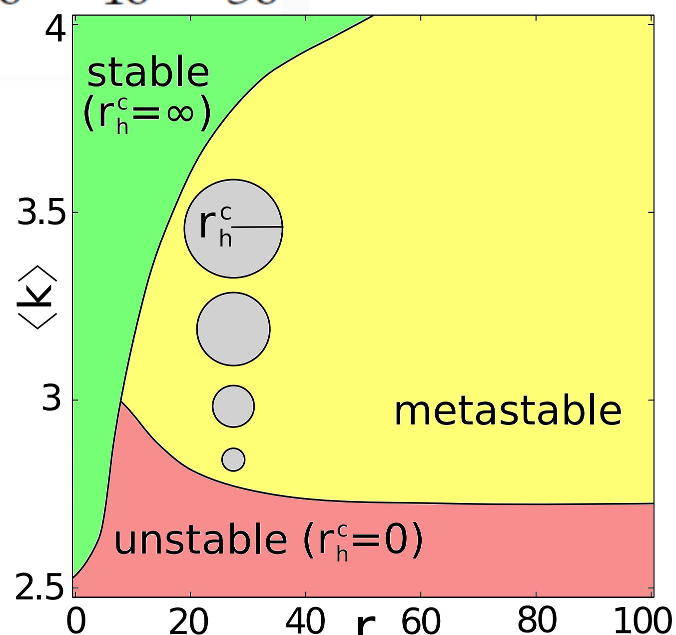
RANDOM FAILURES-Localized attacks

Connectivity Length



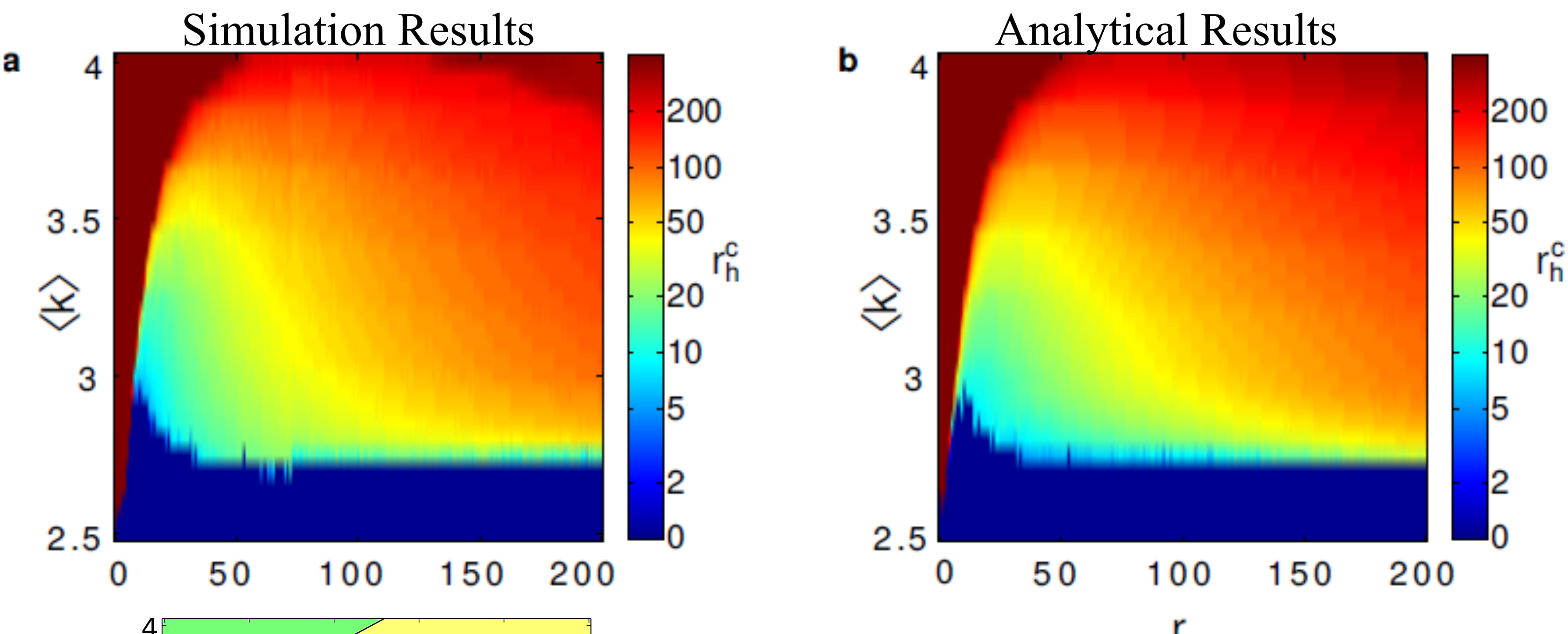
Dependency Length

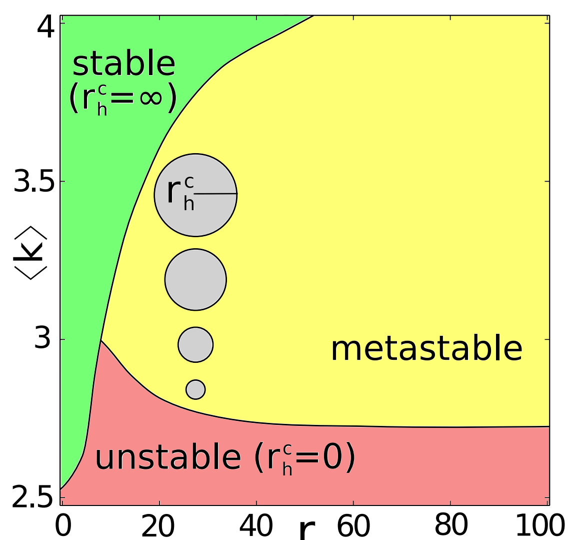


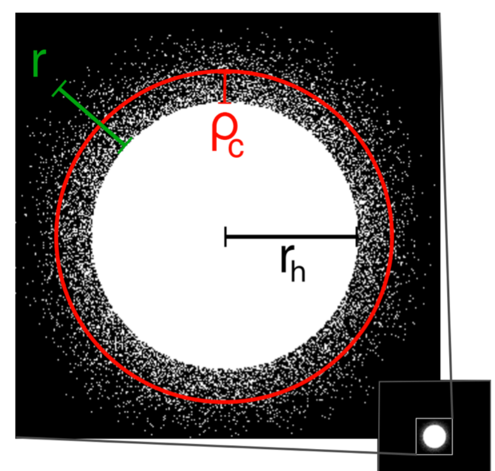


Danziger et al EPL (2016)
Dana Vaknin et al
(NJP, 2017)

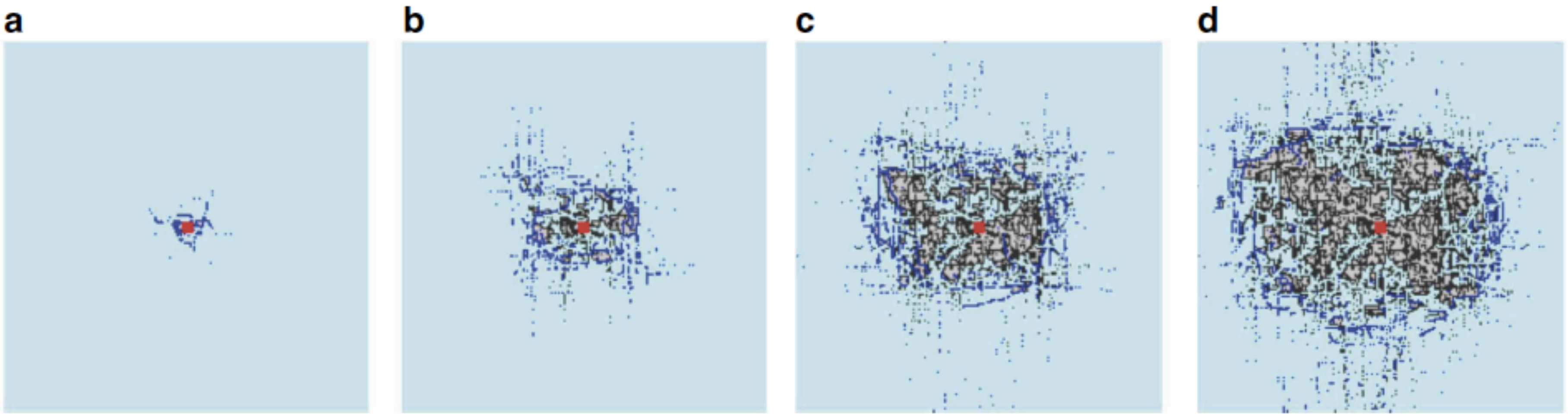
New percolation-localized attacks



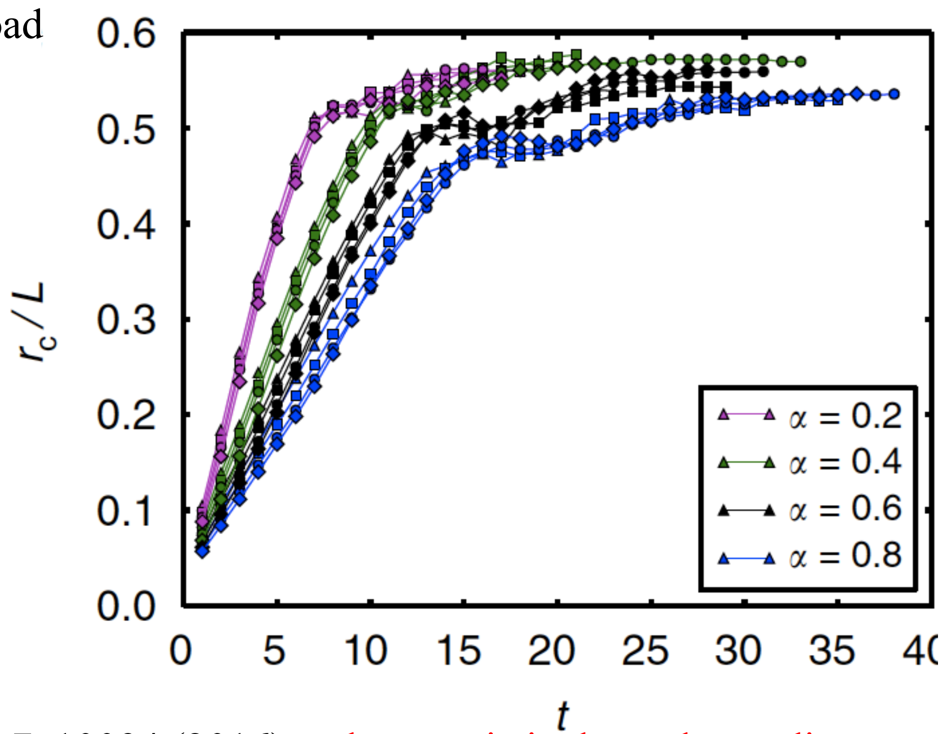


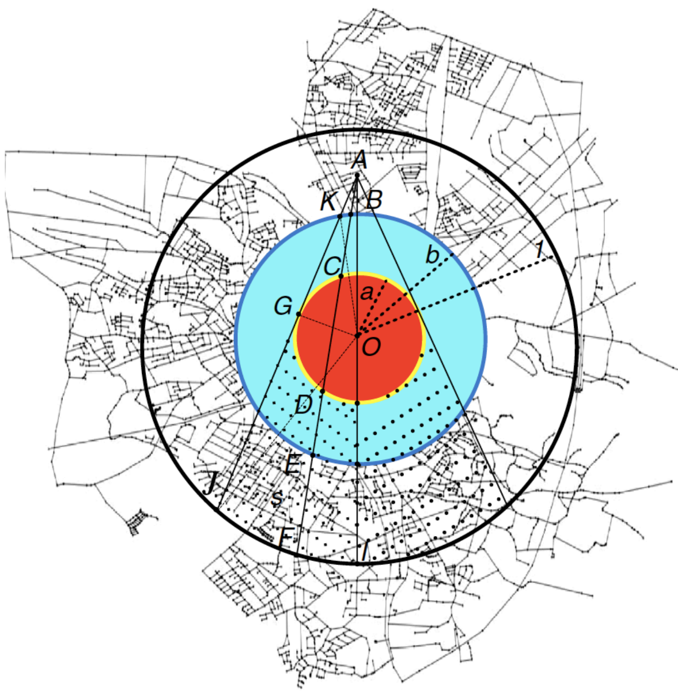


Cascading of Overload Failures-Localized Attack



Motter Overload Model

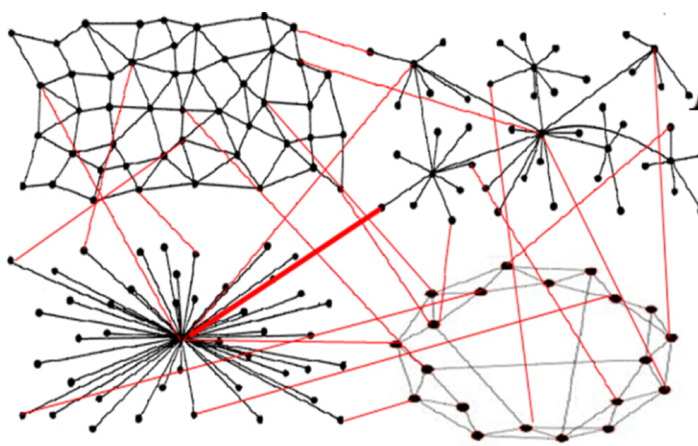


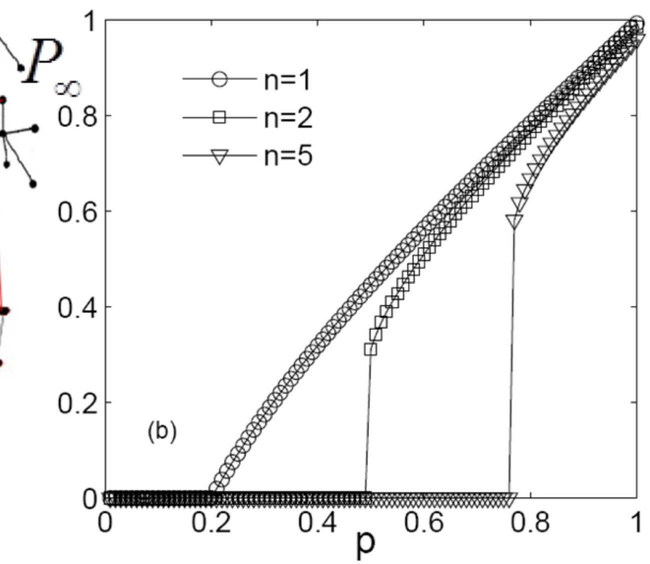


Zhao et al
Nature Comm. **7**, 10094 (2016)—characteristic dependency distance

Summary and Conclusions

- Statistical physics approach for robustness of Networks and of interdependent networks—cascading failures.
- New paradigm: abrupt collapse compared to continuous in single network
- Generalization to "Network of Networks": n interdependent networks- 60y of graph theory and percolation is only the limited case, n=1!
- Spontaneous failure and recovery of system of systems-optimal repairing
- Localized attacks-finite size failure- zero fraction; p_c=1 -- full collapse!!





Buldyrev et al., NATURE (2010)
Parshani et al., PRL (2010)
Gao et al, PRL (2011)
Parshani et al, PNAS (2011)
Wei et al, PRL (2012)
Gao et al., Nature Phys. (2012)
Bashan et al, Nature Phys. (2013)
Daqing Li et al, PNAS (2015)
Majdamzic et al Nat. Phys. (2014); Nature Comm. (2016)
Danziger et al, EPL (2016)
Xin Yuan, Yanqing Hu et al, PNAS (2017)